IEP NEWSLETTER

Interagency Ecological Program for the San Francisco Estuary

OF INTEREST TO MANAGERS

Zach Hymanson (CALFED), zachary@water.ca.gov

Two articles on salmon present findings of interest to managers. Weber and others (page 16) report on a novel technique (analysis of otolith sulfur isotopic ratios) useful as a tool to help identify hatchery-raised salmon and reconstruct nutrition sources, migration, and other aspects of salmon life history. Botsford (page 47) discusses evidence from ocean monitoring that suggests changing ocean conditions (such as El Niño events) have a strong effect on local salmon populations. New tools and insights such as these demonstrate how science is furthering our understanding of the effects anthropogenic and environmental factors are having on California's salmon populations.

We are again reminded of the Sacramento-San Joaquin Delta's dynamic nature. Lucas and others (page 21) report on the results of detailed spatial mapping and short time scale measurements of water quality conditions within a flooded delta island (Mildred Island). Results show basic water quality and chlorophyll *a* concentrations (an indication of phytoplankton biomass) "can vary substantially over spatial scales of hundreds of meters or less ('patchiness') and temporal scales of hours or less ('pulseyness')." Similarly, Orsi (page 27) found variable concentrations and relationships of chlorophyll *a* and zooplankton abundance at six sampling locations within and around Mildred Island. Orsi concludes that physical features such as the number, depth, width, and location of levee breaches, as well as the density of filter-feeding clams will have large effects on whether shallow water habitat is a net importer or exporter of phytoplankton and zooplankton. These articles demonstrate that the highly dynamic and variable nature of the Delta and the resulting pulsey/patchy distribution of chemicals and organisms must be considered in all Delta restoration and civil engineering projects.

Fish entrainment into small Delta agricultural diversions is one source of anthropogenic mortality. Although over 2,200 diversions are distributed throughout the Delta, the magnitude and population level effects associated with small diversion entrainment fish mortality are largely unknown. The lack of appropriate sampling sites is one major reason for the lack of information. Matica and Nobriga (page 32) describe the details of modifications to one agricultural diversion to permit systematic estimates of fish entrainment. A companion article by Nobriga and others (page 34) provides an assessment of the vulnerability to diversion entrainment with a comparison among native and non-native species. Generally, the results suggest entrainment risk is influenced by the presence or absence of a fish screen and by fish habitat use and diel behavior. A detailed understanding of these factors could help managers: (1) assess the need and prioritize locations for fish screens, and (2) recommend alternative strategies to reduce entrainment losses at unscreened diversions. Ultimately, a modeling approach will likely be required to confirm if a large-scale screening program for Delta irrigation diversions is an effective component of a comprehensive restoration strategy.

The IEP continues to refine and improve its monitoring programs to ensure managers are provided with the best data for making informed management decisions. In this regard Souza (page 44) reports on revisions to the DFG spring midwater trawl through comparisons with another sampling method (Kodiak trawl). This springtime sampling targets adult delta smelt to aid in determination of their distribution around the time of spawning. Improving the detection rate of pre-spawning delta smelt should enable IEP scientists to better inform water export operators of the potential to entrain adult delta smelt and the resulting larvae.

EDITORIAL

Pat Coulston (DFG), pcoulsto@delta.dfg.ca.gov

The publication of this issue of the *IEP Newsletter* roughly coincides with the end of the IEP's annual spring–summer period of intense field sampling. Although important monitoring and research activities are conducted throughout the year, it is during the March through July period that the logistical needs of our most important, core fish monitoring efforts (Real-Time Monitoring, Spring Midwater Trawl Survey, Townet Survey, 20-mm Delta Smelt Survey, adult striped bass tagging, and various intense juvenile salmon research and monitoring efforts) place the greatest demands on the program's limited vessel, equipment, and human resources. Now is a good time of year for the IEP managers and supervisors to look back and ask, "How did we do?" Actually, during this era of tightening agency budgets and severe hiring limitations the more interesting question might be: How did we do it?

To the casual observer of the IEP Program, it probably appeared to be "business as usual" in spring, 2002. After all, the critical, time-sensitive tasks such as the near-real time collection and reporting of 20-mm Survey data was largely successful at meeting the information needs of resource agency decision makers. Virtually all of the routine monitoring was completed, adding to highly robust datasets on the status, trends, and functions of the largest estuary on the west coast of North America. So, how did it all get done? There is an old golfing axiom that it is sometimes "better to be lucky than good." In the case of the 2002 spring - summer field season the IEP was definitely *both* lucky and good.

During the last few months of 2001 and the early part 2002, the IEP Program began its preparations for the upcoming intense field season. It is during this time that vessels are "hauled-out" and repaired, lab supplies are ordered, and (perhaps, most importantly) temporary help is interviewed and hired. Unfortunately, by the early winter of 2001–2002 the effects of changed economic conditions, particularly State agency hiring constraints were starting to be felt. Project supervisors reported to managers that it was highly likely that resources would fall short of needs during the critical March through July

period and everyone went to work to try and make the best of it. So, how was the IEP "lucky" and how was it "good"?

Lucky

- The "take" of delta smelt and winter-run chinook at the State Water Project and Central Valley Project intakes never reached critical levels, which obviated the need for supplemental 20-mm Survey runs, and allowed lab staff to both complete sample processing and fill in where needed in field sampling.

- The relative absence of filamentous algal blooms in 2002 generally reduced the effort required to process 20-mm Survey samples and allowed the smaller than normal lab crew to stay on schedule.

- Although there are many troublesome Program-related vacancies within the agencies, IEP's compliment of skilled vessel operators was at near-full strength during this spring-summer field season. Importantly, the critical lead vessel repair and maintenance position at DFG's Stockton office had been recently filled with a highly skilled individual.

Good

- The IEP Agency Coordinators quickly identified program priorities so that staff could focus their project planning and implementation efforts.

- Project supervisors and staff carefully identified planned activities that could be deferred until after the critical field season.

- Staff and supervisors willingly participated in an unprecedented level of cross-project integration to ensure efficient use of resources.

- At critical times our dedicated vessel operators willingly worked many long days and weeks, in particular to facilitate salmon trawling at Mossdale on the San Joaquin River.

- In several cases program staff willingly stepped back into critical field and lab activities from which they had previously promoted or transferred.

- IEP agencies worked collaborative to arrange fund transfers that allowed federal agencies to fill in critical holes with supplemental hires.

It is difficult to overstate the robustness of IEP's multi-agency approach to accomplishing environmental monitoring and research objectives. As with biological systems, a more diverse program is more resilient and able to withstand perturbations. The ability to integrate and swap resources during lean economic times allows work to go forward that would very likely be suspended or cancelled in a single-agency, state-only, or federal-only program. However, challenges remain ahead for the program. Decisions to defer sample processing, analysis, and report writing had the short-term benefit of allowing essential spring-summer field tasks to be accomplished, but chronic deferral will lead to the delayed development of ecological information that may be less urgent, but is no less important for effective management of the estuary.

There is some hope the choices will not be as difficult during the upcoming months. In a clear statement of the Program's importance to decision makers, DFG's Central Valley Bay-Delta Branch recently received a substantial allocation of temporary employee positions through the State's hiring freeze exemption process. A strategic planning process is underway to ensure optimal use of this allocation. Moreover, the dedication, interest, and competence of the IEP's people provide strong assurance that we will again be "good" in 2003—the question is whether IEP will again be "lucky"?

IEP QUARTERLY HIGHLIGHTS

April–June 2002

Neomysis/**Zooplankton Study**
W. Lee Mecum (DFG), lmecum@delta.dfg.ca.gov

Mean spring *Acanthomysis bowmani* sample density increased considerably from 4.8 m^{-3} last year to 9.1 m^{-3} this year, but *Neomysis mercedis* density was zero in spring 2002, compared to 0.35 per cubic meter in spring 2001. As of May 2002, 11 months had elapsed without any *N. mercedis* catch; however, a few were caught in June. *Neomysis kadiakensis* declined somewhat compared to spring 2001.

Differences in copepod densities compared to spring 2001 were mixed. Spring 2002 density of *Limnoithona tetraspina*, the dominant copepod in the estuary, increased from a mean of 3408 m^{-3} for spring, 2001 to 6468 m^{-3} in spring 2002. *Acartia*, *Acartiella,* and *Diaptomus* also increased compared to last year. *Eurytemora*, *Sinocalanus*, and *Acanthocyclops* spring density all declined from last year. The most significant decline, however, was for *Pseudodiaptomus forbesi*, the calanoid copepod which has replaced *Eurytemora* as a major food source for young fish. None were collected this spring. Last spring, mean *P. forbesi* density was around 76 m^{-3}. The other copepods did not show much change relative to spring 2001.

Cladoceran and rotifer density changes were mixed with no major changes except for the rotifer *Synchaeta bicornis*, which dropped from approximately 11 m^{-3} last spring to zero this spring.

Suisun Marsh Salinity Control Gates

Robert Vincik (DFG), rvincik@delta.dfg.ca.gov

The second year of a planned three-year study of adult chinook salmon passage at the Suisun Marsh Salinity Control Gates (SMSCG) in Montezuma Slough is planned to begin at the end of September 2002. Using methods described in the 2001 study, salmon will be implanted with ultrasonic transmitters and monitored for upstream migration during three SMSCG operational phases. The study will focus again on adult salmon use of the existing boat lock for upstream passage.

The SMSCG three operational phases for 2001 were:

- Phase I: Gates open, flashboards out, boat lock closed. September 24 through October 6.

- Phase II: Gates operating, flashboards in, boat lock open. October 7 through 20.

- Phase III: Gates operating, flashboards in, boat lock closed. October 21 through November 3.

Results from the 2001 study, reported in the previous issue of the *IEP Newsletter*, showed a higher percentage of fish passage for Phase II when compared with Phases I and III (Vincik 2002). These preliminary results indicate the feasibility of using the boat lock for salmon passage at the SMSCG.

The operational phases will be repeated in a different order for 2002, and the results compared with last year's study for trends in fish passage at the SMSCG.

Reference

Vincik RF. 2002. Adult chinook salmon migration monitoring at the Suisun Marsh Salinity Control Gates, Sept.–Nov. 2001. IEP Newsletter 15(2):45–8. Available via the Internet: http://www.iep.ca.gov/report/newsletter

San Francisco Bay Fish Monitoring

Kathy Hieb (DFG), khieb@delta.dfg.ca.gov

The IEP, through DFG's San Francisco Bay Study, has been sampling fishes and macroinvertebrates monthly in the bay since 1980. As San Francisco Bay is situated in a transition zone between cold-temperate marine fauna (north of Pt. Blanco) and subtropical marine fauna (south of Pt. Conception), we collect species from both faunas. During warm water periods, such as from 1976–1998, catches of subtropical species, including Pacific sardine, California halibut, and white seabass, increased. In 1999, the central California coastal zone went through a "regime shift," and is now in a cool water period. Dungeness crab, Pacific herring, and English sole, all cold-temperate species, continued to have very strong year classes in 2002 (see below). This spring we collected age-0 lingcod and kelp greenling, also cold-temperate species, although the numbers were not as great as in spring 2001. Although the last El Niño event ended in 1998, we continued to collect older Pacific sardine and California halibut, and a few California grunion (another subtropical species) in 2002. No local recruitment of California halibut has been detected since 1998 and we collected only age 4+ halibut in 2002.

Spring catches are a preliminary indication of year class strength for many species, although we often use at least six months of data to calculate an annual abundance index. The first age-0 Dungeness crabs of the year were collected in March, which is very early for this species and indicative of a strong year class. The May-June total catch of age-0 Dungeness crabs was 632. This is the third greatest May-June catch for the study period; the greatest catches occurred in 1988, followed by 2001. In May and June 2002, age-0 Dungeness crabs were widely distributed from lower South Bay to upper San Pablo Bay and Carquinez Strait. The highest catches were at our Central Bay channel stations in June, as small crabs were still immigrating from the Gulf of the Farallones.

The age-0 Pacific herring April-June 2002 catch was slightly greater than that of 2001. It appears that the 2002 Pacific herring age-0 annual abundance index will be similar to the 2000 and 2001 indices, which were the greatest since 1986. This year most age-0 Pacific herring were collected from South Bay, north of Oyster Point, to

lower San Pablo Bay, with a few fish as far upstream as Suisun Bay and Chipps Island.

We have observed successive record age-0 English sole indices in the bay over the past three years. Age-0 English sole were widely distributed this spring, with >100 fish per tow from stations near the San Mateo Bridge in South Bay to stations in lower San Pablo Bay. If below average ocean temperatures and strong upwelling persist for several years, we will continue to collect large numbers of these and other cold-temperate species in the bay. For more information about west coast ocean conditions, please see the NOAA El Niño Watch page on the Internet at http://cwatchwc.ucsd.edu/elnino.html. The central California coast regional sea surface temperature anomaly can be viewed at http://cwatchwc.ucsd.edu/time_series.html.

Delta Resident Shoreline Fish Sampling

Dennis Michniuk (DFG), dmichniuk@delta.dfg.ca.gov

An integral part of the Delta Resident Shoreline Fish Sampling is the annual tagging of largemouth bass (*Micropterus salmoides*) with reward tags to encourage angler returns. Largemouth bass have been tagged with Peterson disc dangler tags below the dorsal fin from 1980 to 1985 and in 1995, 1997, 1999, and 2001. Tagging occurred both within the resident fish sampling sites and also during roving tagging operations. The recapture of these tags will be used to estimate survival and determine angling and natural mortality rates.

In 2002, 408 largemouth bass were tagged between March 25 and April 17. Reward tag values varied from no reward to $200. Only those fish with a total length greater than 300 mm were tagged. These largemouth bass were tagged throughout the Delta: 53 in the south Delta, 150 in the central Delta, 137 in the east Delta, 51 in the west Delta, and 17 in the north Delta. Of the total bass tagged (408), 31 were tagged within the randomly chosen Delta Resident Shoreline Fish Sampling sites and 377 were tagged in other areas.

This quarter, anglers have recaptured and reported 66 of the 2002-year tags, 11 of the 2001-year tags, and 2 of the 1999-year tags.

Juvenile Chinook Salmon Monitoring

Rick Burmester (USFWS), rburmest@delta.dfg.ca.gov

USFWS Stockton Fish and Wildlife Office (STFWO) staff monitored juvenile salmon and other resident species in the spring, implementing some changes from the fall. On January 29, the Sacramento area beach seine concluded for the season; the Sacramento trawl changed from Kodiak to midwater gear at the end of March; the Chipps Island trawl conducted double shifts (ten tows, twice a day) for VAMP studies between April 4 and May 28; and the lower San Joaquin River beach seine sampling was restricted to the lowest three sites in June due to low flows.

Winter-run sized chinook salmon[1] were last detected entering the Delta on February 12 in the lower Sacramento River beach seine. In the Sacramento area, the Kodiak trawl last detected these fish on February 23, and then at Steamboat Slough (North Delta beach seine) on February 25. At Chipps Island, the last winter run was captured on May 21.

Yearling-sized, late-fall run chinook were last detected entering the Delta on January 8 in the Sacramento River Kodiak trawl. No late-fall run were captured again until June 4, when four young-of-year fish were caught in the North Delta beach seine.

Fall/spring-run sized chinook were last captured in the lower Sacramento River beach seine site on May 21. These fish continue to be captured in the North Delta, the Sacramento River, and at Chipps Island. Only one fall-run fish was taken in the San Francisco/San Pablo beach seine for the season.

While 4,454 fall-run chinook have been captured in the Mossdale Kodiak trawl, only two of these fish were captured before hatchery releases in April. The lower San Joaquin River beach seine captured only three fall-run fish, the lowest number since this route began in 1994. A total of 47 wild steelhead (not ad-clipped) was captured since December, two in the Sacramento Kodiak trawl, six in the Mossdale Kodiak trawl, and 40 at Chipps Island.

---

1. Juvenile chinook salmon race designations are based on Delta curves of Greene's modification of the Fisher size criteria.

Also at Chipps Island, 13 white sturgeon were captured ranging from 500 to 1,600 mm FL.

For a review of the STFWO monitoring program, see the Delta Juvenile Fish Monitoring Program at http://www.delta.dfg.ca.gov/usfws/.

Splittail Early Life History Study

Fred Feyrer (DWR), Ted Sommer (DWR) and Randy Baxter (DFG), ffyrer@water.ca.gov

This study is designed to obtain information on growth, feeding, distribution, and habitat associations of young-of-year (YOY) splittail. Additionally, we are collaborating with Dr. Bernie May (UC Davis) who will be examining the population genetic structure of splittail from samples collected during this study.

Field sampling started in April is conducted primarily with beach seines and is ongoing. We sample the Sacramento River, Butte Creek/Sutter Bypass, Yolo Bypass, San Joaquin River, interior Delta, Napa River, and Petaluma River. Collections also have been made at other locations with the help of many colleagues: Sutter Bypass (Tracy McReynolds, DFG); Cosumnes River (Pat Crain, UC Davis), Suisun Marsh (Robert Schroeder, UC Davis); the CVP fish salvage facility (Brent Bridges, USBR); and the SWP fish salvage facility (Jim Odum, DWR).

To date, significant numbers of YOY splittail have been collected at most of the field locations. Young-of-year splittail first appeared in our samples in mid-May; the catches strongly suggest spawning occurred primarily outside of the Delta. Large numbers of YOY splittail have been collected from very shallow intertidal habitats.

In the coming months, work will begin on extracting and mounting otoliths to estimate daily growth rates and examining gut contents for food habits. The samples will then be turned over to Dr. Bernie May for the population genetics work.

NEWS FROM AROUND THE ESTUARY

Investing in the IEP Environmental Monitoring Program

Anke Mueller-Solger (DWR) and Zachary Hymanson (CALFED), amueller@water.ca.gov

As reported in previous issues of the *IEP Newsletter* (1/2001, 4/2001), the Interagency Ecological Program's Environmental Monitoring Program (EMP) is undergoing a comprehensive programmatic review. Funded through IEP by the Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (USBR), the EMP has monitored water quality and lower trophic level organisms in the upper San Francisco Estuary in compliance with consecutive water right decisions D-1379, D-1485, and D-1641 for more than 30 years. The goal of the ongoing review is "to recommend a balanced, scientifically sound, implementable environmental monitoring program design to fulfill water right permit conditions and address the needs of current and potential users identified during this review." To achieve this goal, we employed a multi-tiered approach involving a core group of agency scientists, invited technical experts working in four subject area teams (SATs), stakeholder representatives participating in three all-participant meetings, and the IEP Science Advisory Group (SAG).

At this time, the SATs, meeting participants, and the IEP SAG have completed their reviews of the water quality, zooplankton, phytoplankton, and benthos components of the EMP. A second draft report synthesizing results from the SATs and the all-participant meetings has been completed. This report contains discussions of monitoring review and design issues as well as plans for a revised monitoring program and specific special studies. We have given presentations based on these draft reports at the IEP Workshop in February 2002, as well as at the National Water Quality Monitoring Council Conference, held in

Madison, Wisconsin, in May 2002. (See website at http://www.nwqmc.org/.)

A final draft synthesis report will address the more recently completed SAG review as well as comments received after a presentation at the IEP monitoring forum on June 19, 2002. This draft report will be submitted to the IEP Management Team and Coordinators and eventually to DWR and USBR managers and the State Water Resources Control Board for review and approval. Pending these approvals, implementation of program revisions and accompanying special studies could begin as early as January 2003.

According to the recently completed IEP SAG review, the EMP is an overall remarkably successful monitoring program. It has provided invaluable data and information about the San Francisco Estuary. The SAG members suggested however that the program benefit from more specific aims and more emphasis on its products. The aims should follow the original EMP mission, guide its design, and focus its products. They also recommended that EMP data should be more rapidly and reliably turned into more useful products through increased "human intellectual investment."

Previously completed review steps and more recent discussions among EMP review core team members and participants in the IEP monitoring forum regarding the SAG review have yielded suggestions about how to address the SAG comments. These suggestions are briefly summarized here.

We propose a hierarchy of primary, secondary, and tertiary program goals according to their specificity and overall relevance. The current and original primary goal of the EMP is given in water right decision D-1641: ensure compliance with water quality objectives and identify water quality and ecological changes ("status and trends") potentially related to water project operations. This is a broad goal, and thus calls for the most comprehensive program design feasible with the existing resources.

Several secondary, more specific goals can be defined based on existing knowledge about the estuary. Specifically, these goals are derived from processes, response variables, and applications recognized to be of particular importance in the upper San Francisco Estuary:

1. Characterize spatial and temporal variability in constituents in terms of hydrodynamic transport processes (Burau and others 2000).

2. Differentiate water project effects by sufficiently monitoring variability in factors and processes other than water project operations.

3. Describe spatial and temporal patterns of variability for salinity (for compliance and export water quality) and water temperature (for fish energetics modeling and management).

4. Provide baseline data for civil engineering and habitat restoration projects (for example, CALFED projects).

A third level of program goals directly will define specific program products by asking specific questions. These questions should be answered by the EMP at appropriate intervals (either defined by physical or biological processes or by management issues and legal obligations) and as rapidly as possible using traditional (reports, newsletter contributions, journal publications) as well as more innovative communication media (interactive web sites). We are identifying the most useful set of questions and products and we welcome suggestions. To be successfully answered, some of these questions will require specific program design. For example, estimating regional (Delta-wide) concentration averages requires appropriate representation of sub-regions characterized by similar concentration levels, while exploration of regional constituent dynamics requires stratification by similar temporal patterns irrespective of concentration magnitudes. The challenge, then, is to properly define, synthesize, and prioritize potentially incompatible program designs.

Proposed EMP design revisions address the goals identified to date and are based on available information about system variability derived from EMP, other monitoring data, and "special studies" conducted over the past three decades. Consistent long-term, low-intensity monitoring has shown significant trends in a number of monitored variables over three decades and has enabled conclusions about the mechanisms responsible for the observed trends (see Jassby and others 2002). More short-term, high-intensity sampling has shown impressive variability in important system attributes at small spatial and temporal scales (see Lucas and others, this issue,

p. 18). To better capture this small-scale variability while maintaining the valuable long-term program continuity, the revised EMP will place much greater emphasis on continuous monitoring in space and time, while preserving the long-term monitoring network. Specifically, specific conductance (SC) and water temperature will be continuously monitored at all EMP stations in the upper estuary. In addition, vessel-based, flow-through measurements of SC, turbidity, dissolved oxygen, and chlorophyll *a* between fixed stations will provide high spatial resolution for these variables during near-monthly monitoring cruises. Some fixed stations also include sensors for additional variables such as turbidity, pH, dissolved oxygen, and chlorophyll *a*. Discrete sampling for the remaining EMP constituents will largely be carried out during routine maintenance of the continuous monitoring stations at alternating spring and neap tides. In some cases, procedural changes for sampling or sample analysis have been recommended and will be considered for implementation.

Hydrodynamic conceptual models of the upper estuary provide the basis for fixed station placement in the revised program design. Continuous monitoring stations will be located within a tidal excursion of neighboring stations and near important bottom features (sills, cells) in the deeper, western estuary. To preserve monitoring continuity, the hydrodynamically determined stations are matched to the greatest possible degree with historical EMP stations. Overall, there will be greater spatial consistency among program elements. Redundancies with other programs will be investigated and, wherever possible, eliminated. The resulting design will continue to yield valuable long-term monitoring data. In addition, it will now generate higher frequency data, which will enable data analysis at the transport (tidal) time scales and therefore better assessments of water project operations effects, which primarily affect the movements of water within the Delta and into the bay. Thus, for fairly non-reactive constituents such as SC, knowledge of the tidal excursions from flow data will allow us to obtain estimates at almost any point in the system. For more reactive constituents such as plankton organisms or dissolved oxygen, local processes (such as grazing, respiration) may significantly contribute to their variability in space and time, and purely hydrodynamics-based extrapolations may be less successful. For these constituents more studies are needed to investigate their small versus larger scale variability in various regions of the estuary, and the resulting ability to extrapolate between stations and sampling events or to compute regional averages. Such studies (funded and carried out through the EMP and/or with additional resources and collaborators) have been identified and prioritized in the program review, and several have already been initiated.

Three study proposals related to the EMP design were presented at the recent IEP monitoring forum. One of these included a feasibility study of the planned expansion of the EMP zooplankton monitoring element into the San Francisco Bay, which will fill an important gap in the current comprehensive Bay and Delta monitoring network. A proposal to investigate the applicability of high-density, spatially integrative monitoring of some constituents (SPM/turbidity, DOC, chlorophyll *a*, temperature) using remote sensing techniques also was discussed at the monitoring forum. Independent CALFED studies will provide further vital insights into variability of several constituents at various spatial and temporal scales (for example, studies headed by J. Cloern [ERP-01-N20] and A. Jassby [ERP-02-207]). In addition, routinely recorded, vessel-based, horizontal profiling data will be used to test how well the fixed station data represents the cross-sectional average.

Clearly, implementation of the proposed program revisions and related special studies require a considerable investment of resources. These investments will come through resource reallocations within the program and through more collaboration and/or competitively obtained outside funding (IEP, CALFED). Fortunately, the EMP has recently been able to increase its human intellectual investment by hiring more senior program staff dedicated to improving its design and products. In addition, the EMP continues to rely on constructive inputs from IEP members, stakeholders, and the interested public.

For comments or to obtain more information, please contact Anke Mueller-Solger, amueller@water.ca.gov, or see the EMP web site at http://iep.water.ca.gov/emp/.

Acknowledgments

Burau and Erwin Van Nieuwenhuyse for helpful comments on this article.

References

Burau JR, Monismith SG, Stacey MT, Oltmann RN, Lacy JR, Schoellhamer DH. 2000. Recent research on the hydrodynamics of the Sacramento-San Joaquin River Delta and North San Francisco Bay. IEP Newsletter 13(2):45–53. Available via the Internet at: http://www.iep.ca.gov/report/newsletter

Jassby AD, Cloern JE, Cole BE. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. Limnol Oceanog 47:698–712.

Lucas L, Schraga T, Lopez C, Burau J, Jassby A. 2002. Pulsey, patchy water quality in the Delta: implications for meaningful monitoring. IEP Newsletter [this issue].

Tidal Datum Determination for Marsh Restoration Planning

Callie Harrison and Chris Enright (DWR), callieh@water.ca.gov

Background

Land and water surface elevations are key physical variables in Suisun Marsh wetland planning and management. Establishing the relationship between the land surface and adjacent channel tide height is a fundamental need for wetland restoration design, planning levee program elements, updating ownership management plans, and accurate computer simulation modeling. In support of these activities, the California Department of Water Resources (DWR), Suisun Marsh Branch has undertaken a cooperative project with the National Oceanic and Atmospheric Administration's National Ocean Service (NOAA NOS) to obtain the necessary knowledge and skills to determine tidal datums following the NOS' accepted procedures and methods.

Both accurate tidal datums and land surveys are needed to determine the relationship between tidal water surface elevations and neighboring land surface. Tidal datums are local vertical index statistics that describe the variation of the tide at a particular location. Standard NOS tidal datums include mean lower low water (MLLW), mean low water (MLW), mean sea level (MSL), mean high water (MHW), mean higher high water (MHHW), and other sea level descriptors. Figure 1 shows a typical interface between tidal datums and land surface for (a) a leveed slough, and (b) a restored or natural marsh. When determining tidal datums, oceanographers use averaging techniques over the 19-year tidal epoch.

DWR's Survey Unit employs licensed surveyors to determine highly accurate land surface elevations. However, DWR has not in the past measured tidal datums. By learning and following the NOS standard procedures, DWR and other participants, including USGS staff, can determine accurate and defensible tidal datums as needed in the future.
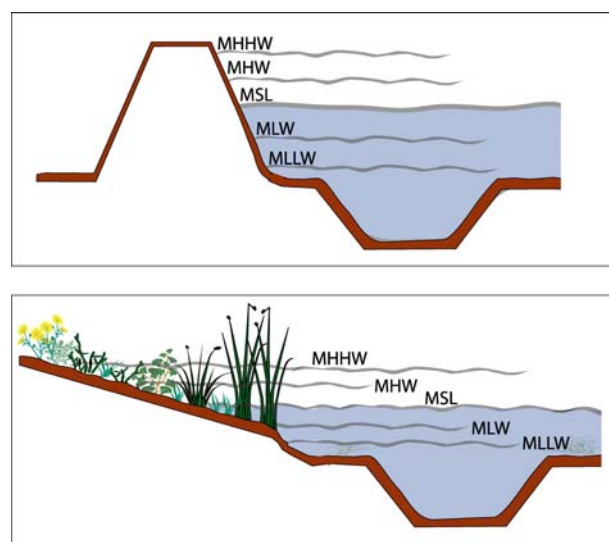

Figure 1 Relationship between tidal datums and land surface (not to scale)

Application of Tidal Datum Information in Wetland Restoration Planning

The Suisun Marsh is part of the San Francisco Bay Estuary, located east of the Bay and west of the Sacramento-San Joaquin Delta. Suisun Marsh is located north of Suisun and Grizzly bays (see location map, Figure 2).

DWR's Suisun Marsh Branch is initiating investigations into the restoration of various properties within the Suisun Marsh to tidal or muted-tidal marsh to meet CALFED ERP goals under the Suisun Marsh Charter Plan. Since the ecology, biology, hydrology, and related functioning of a marsh are highly dependent on the relationship between land and tidal water elevations, it is critical that accurate tidal ranges are established at restoration sites in the early stages of planning.
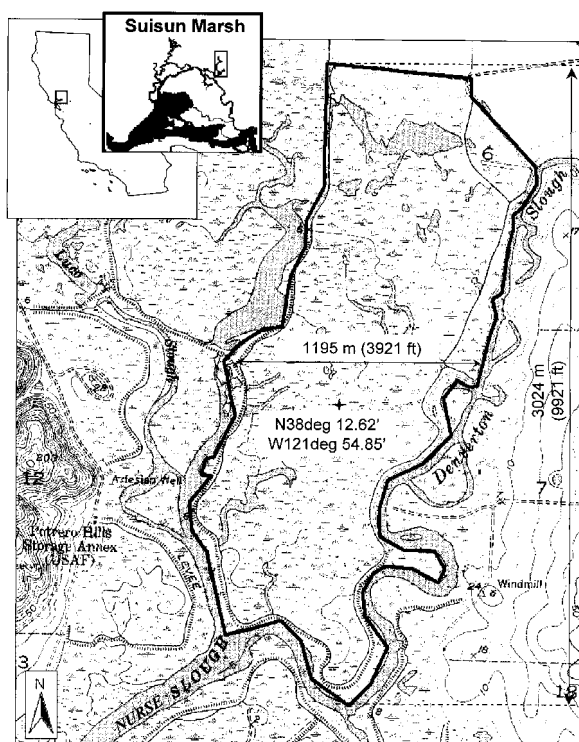
Figure 2 Location of the Denverton Club in the northeast Suisun Marsh. Parcel totals approximately 760 acres.

Often the relationship between the interior land and the nearby tidal range will determine the type of marsh restoration that is most appropriate for that site. For example, lands at or near MSL are likely appropriate for restoration to full tidal action. On the other hand, subsided lands might be more appropriately restored as muted-tidal marsh, since allowing full tidal access to these areas would result in shallow baylands with limited habitat value and species richness. Thus, the continuum of restoration options to meet species recovery goals depends on establishing land and water elevation relationships.

Demonstration Project for Tidal Datum Determination Procedures

A location in the Suisun Marsh was selected as a learning and demonstration site for tidal datum determination. DWR and NOS are approaching the demonstration as if a tidal marsh restoration were planned at a managed wetland in the area. In this way, all steps involved in the tidal datum determination process as it pertains to wetland restoration planning will be completed.

The Denverton Club in the northeastern portion of the Marsh (figure 2) was selected for the demonstration project. The property is approximately 760 acres comprised of managed wetlands transitioning into uplands and includes both high and low marsh. At this time it is managed as a waterfowl hunting club with portions flooded from October to February. The property is bounded by tidal sloughs (Denverton, Nurse, and Luco Slough) and receives freshwater flow from upstream Denverton Creek.

A reconnaissance visit to the site by the joint DWR/NOS team occurred in April 2002. The project will continue until approximately winter 2003.

Determining Tidal Datums for Marsh Restoration

The demonstration project will include the following steps, which are necessary to obtain an accurate estimate of tidal range.

1. **Establish a tide station and benchmarks.** A network of tidal stage stations will be established, including re-occupation of a historical NOS station at Bradmoor Island, Nurse Slough. Two tide stage loggers will be operated for three months near the Denverton property, one on Denverton Slough, and the other on Nurse Slough. The historical station will be operated for a period of one year. Benchmarks will be established at each station to allow for tie-in to the North American Vertical Datum of 1988 (NAVD88).

2. **Compute tidal datums and establish tidal datums on the marsh surface.** Simultaneous comparisons of the tidal elevations between the network stations and the NOS long-term, primary station at Port Chicago

will allow for determination of the local equivalent tidal epoch (19 year) means.

3. **Establish a geodetic datum connection.** In order to tie-in the measured relative stage data to actual elevations in NAVD88, surveys will be made to existing benchmarks of known elevation.

4. **Create a digital elevation model (DEM) of the marsh surface.** Topographic surveys of the Denverton property will be made to create an appropriate resolution DEM.

5. **Perform frequency and duration analyses on the observations relative to the marsh surface.** The DEM coupled with the tidal datum information will allow for computations of length and depth of flooding on the property were it to be restored to tidal action. This information also could be used to design the planned marsh surface for an appropriate tidal flooding regime.

Through participation in this demonstration project, DWR and others will learn to accurately produce tidal datum information for use in wetland restoration. Also, this knowledge is transferable to many other purposes including levee program planning, ownership management planning, and computer modeling.

DAYFLOW Program Updates

Brad Tom, Kate Le, and Chris Enright (DWR), cenright@water.ca.gov

Introduction

The DAYFLOW (hereafter, Dayflow) Program has been updated to reflect changing conditions in the Delta and agency corrections to the input data. Historical Dayflow output has been adjusted by updating calculations with corrected Sacramento River flow data and by modifying the computational scheme. Dayflow parameters and definitions also were adjusted. The Dayflow web site includes complete updated documentation of the computational scheme. Previous Dayflow documentation also is available at the site.

All Dayflow users are encouraged to replace their current output files with the updated files now available on-line at

http://www.iep.water.ca.gov/dayflow/ where additional modification details are available.

Specific adjustments to the parameters, associated effects, and web sites updates, are described below.

USGS Data Updates

Sacramento River flow (QSAC) values were corrected using updated data from USGS. Flow data for 50 days since 1955 have changed. Water quality and daily streamflow data from a CD-ROM published in 1996 are posted at http://water.usgs.gov/pubs/dds/wqn96cd. The data were based on a late 1994 retrieval of measurements that were available on the USGS District computers at that time. This was the official USGS flow data for Sacramento River flow. More recent retrievals of historical data from the USGS includes several updates, and should supersede previous published measurements such as those reported in the USGS Digital Data Series *DDS-37: Data from Selected U.S. Geological Survey National Stream Water-Quality Monitoring Networks*. For more information on this data series, see the web page http://water.usgs.gov/pubs/dds/.

Historical flow data for Sacramento River inflow to the Delta comes from two gauges:

1. Sacramento River at Sacramento, station number 11447500, October 1, 1955 through September 30, 1979[1]

2. Sacramento River at Freeport, station number 11447650, October 1, 1979 through present[2]

Table 1 lists summary change statistics for the 50 days of data that were updated. Mean and maximum values were calculated using absolute values of changes.

See http://www.iep.water.ca.gov/dayflow/ for an expanded explanation of updates based on USGS data changes.

---

1. data available at:
   http://water.usgs.gov/nwis?program=discharge&site_no=11447500&agency_cd=USGS

2. data available at:
   http://water.usgs.gov/pubs/dds/wqn96cd/html/wqn/wq/region18/11447650.htm

Table 1 Summary statistics for QSAC flow data changes

Statistic	Flow (cfs) or Percent change (%)
Mean change	1489 cfs
Maximum change	27000 cfs
Mean percentage change	4.0%
Maximum percentage change	30.3%

Computational Scheme Updates

For water years 1956–1996, Cosumnes River flow and Mokelumne River flow were included in QMISC (Miscellaneous Stream Flow) instead of QEAST (Eastern Delta Inflow). QMISC was adjusted by subtracting Cosumnes River flow and Mokelumne River flow. Since QEAST includes QMISC, no other adjustments were necessary.

The definition of QSWP was changed from "Clifton Court Inflow – BBID" to "Banks Pumping." Delta Cross Channel (DXC) operation data times were adjusted from Pacific daylight time (PDT) to Pacific standard time (PST). All calculations that use QSWP, and DXC were updated. Calculated values that changed as a result include QEXPORTS, QXGEO, QWEST, QRIO, QOUT, EXPIN, QDIVER, QEFFECT, and QEFFDIV. For variable definitions and expanded explanation, see http://www.iep.water.ca.gov/dayflow/.

For water years 1956–1996 the values of QWEST and QRIO were updated when it was discovered that the equations used in the previous release did not include QMISDV.

See http://www.iep.water.ca.gov/dayflow/ for an expanded explanation of updates for water years 1956–1996 that occurred as a result of computational scheme changes.

In the future we expect further improvements to the Dayflow program as new direct flow measurement data become available. For example, the Dayflow computational scheme will be updated when continuous flow monitoring begins in the Delta Cross Channel. The parameter QXGEO, an estimate of Georgiana Slough and Delta Cross Channel flow, will become obsolete and will no longer be used when Delta Cross Channel flow data become available. As more direct flow measurements become available, the accuracy and reliability of Dayflow output will continue to improve. All Dayflow users are encouraged to replace their current output files with the updated files and additional modification details are now available at http://www.iep.water.ca.gov/dayflow/.

Dayflow Website Update: Net Delta Outflow vs. Net Delta Outflow Index

A primary output of Dayflow is an estimate of Net Delta Outflow, often referred to as Net Delta Outflow Index (NDOI). This is an arithmetic summation of river inflows, precipitation, agricultural consumptive demand, and project exports. The USGS has established a network of flow monitoring stations in the Delta. Using flow monitoring data from Rio Vista, Three Mile Slough, Jersey Point, and Dutch Slough, a direct estimate of Net Delta Outflow (NDO) is now available. The plots below compare NDO and NDOI.

NDOI is designated by the Dayflow parameter QOUT, which is defined as:

QOUT = QTOT + QPREC – QGCD – QEXPORTS – QMISDV

NDO, which is not a Dayflow parameter, is a direct estimate of daily average flow based on 15-minute USGS ultrasonic velocity meter (UVM) flow data from the IEP tributaries database. NDO was calculated as the sum:

NDO = Rio Vista + Three Mile Slough + Jersey Point + Dutch Slough

where Rio Vista = Sacramento River at Rio Vista UVM; Three Mile Slough = Three Mile Slough at San Joaquin River UVM; Jersey Point = San Joaquin River at Jersey Point UVM; and Dutch Slough = Dutch Slough at Jersey Island UVM.

Figure 1 shows NDO vs. NDOI for water years 1996–2000. Note that NDO is not shown for times when Rio Vista, Three Mile Slough, Jersey Point, and Dutch Slough UVMs were not in simultaneous operation.
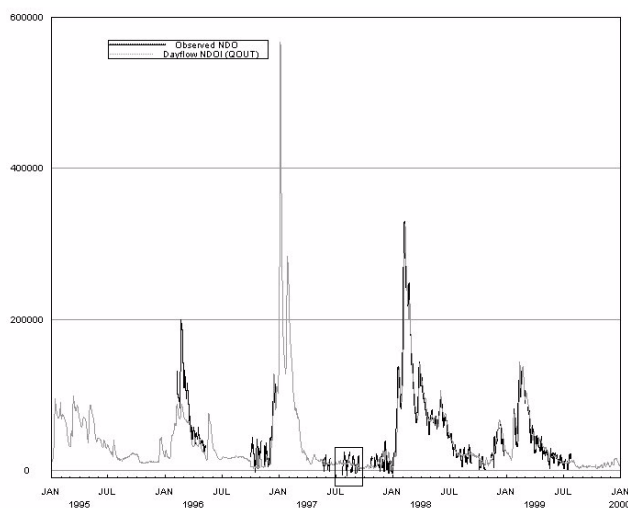
Figure 1 Comparison of NDO and DAYFLOW NDOI: WY 1996–2000

Figure 2 shows a small portion of Figure 1 (July 17, 1997 through September 21, 1997). Moon phases are included to show the effects of the spring-neap cycle. The period averages of NDOI and NDO are nearly the same. However, the astronomical forcing of the sun and moon cause the Delta to fill and drain over approximately 14 days. When superimposed on the effect of riverine inflow and project operations as estimated by Dayflow NDOI, the spring-neap cycle can lead to short periods of negative NDO. Users of Dayflow output should be aware of this limitation.
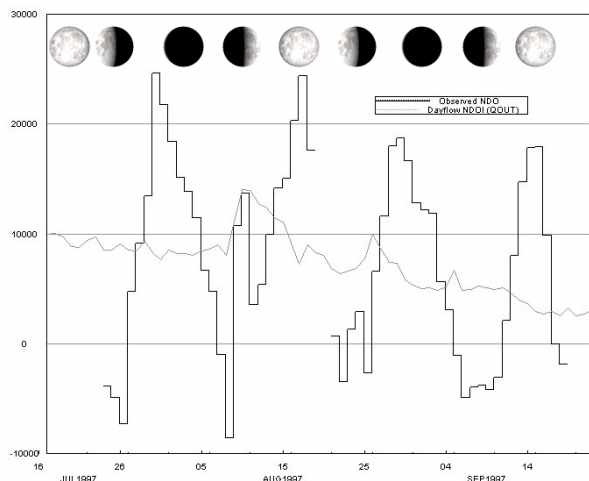
Figure 2 Comparison of NDO and DAYFLOW NDOI: July 17, 1997 through September 21, 1997. Effects of the spring (new and full moons) neap (partial moons) cycle. Moon graphics provided by U.S. Naval Observatory at http://tycho.usno.navy.mil/vphase.html

Do Mitten Crabs Carry the Parasitic Lung Fluke?

Johnson Wang and Lloyd Hess, jwang@mp.usber.gov

On a visit to California in 1999, Professor Nai-Gong Zhao, a Chinese expert on mitten crabs, insisted that the Chinese mitten crab does not carry the lung fluke. He further remarked that he would be very surprised to learn that the mitten crab introduced to California carried the lung fluke. To date, no lung flukes have been found in California mitten crabs.

One of us (Dr. Wang) was perplexed by this seeming inconsistency in the literature—some reports indicating mitten crabs were the host of lung flukes; and others, at the insistence of Chinese fishery professionals, that the crabs do not carry lung flukes. Dr. Wang hired Professor Zhang, Lie-She (retired) of the Shanghai Fishery Research Institute to investigate the controversy. In the following letter, Professor Zhang gives his knowledge and response on the matter.

Dear Dr. Johnson Wang:[1]

The following are some references on creek crab [that] you inquired about in the previous letter:

1a. There are approximately 1,000 species of the creek crab in the world. Distribution ranges are in Asia, America, Europe and Africa. In China, we have approximately 200-300 species. There are two families of the creek crab: Potamidae and Sinopotamidae. Their representative genus includes *Potamon* and *Sinopotamon*, and their representative species are *Potamon denticulatus* and *Sinopotamon yangtzekiense*.

1b. The creek crab is the lung fluke parasite carrier. Host includes human and other mammals. The disease is known from the eastern part of Asia, southeast Asia and China (Manchuria, Sechan, Yunan, Zejiang, Jiangsu, and Anhui provinces). [The] name of the lung fluke parasite is *Paragonimus westermani*. [The] adult stage of this parasite is [found] in the human lung, tiger, leopard, and other mammal[ian] lung's

---

1. Correspondence in Chinese, copies of original letter are available by request of the addressee.

[sic]. The eggs of the parasite [are] discharged from mouth or droppings by the host and fall into the water and hatch as larvae. The larvae enter the body of a freshwater snail, the first intermediate host, such as *Semisuloospira*. The parasites move out of the snail, and enter the body of the creek crab as the second intermediate host. Human and other mammals eat the parasite infected creek crab and become the final host. Initially the parasite enters the host's digestive tract and break through the intestinal wall and enter the lung tissue as the final niche. Both the freshwater snail and creek crab prefer the fast-running creeks where the creek water has high oxygen content.

2. The Chinese mitten crab, *Eriocheir sinensis*, lives in a totally different environment than the creek crab, namely the river, lake, and pond habitat. The freshwater snail, or the first intermediate host, is not found in this environment, and the Chinese mitten crab does not carry the lung fluke parasite. Furthermore, anatomical analysis of mitten crab tissue has not found parasites. The conclusion is that the Chinese mitten crab does not carry the lung fluke parasite and is suitable for human consumption. (It is possible that the Chinese creek crab was wrongly translated as Chinese hairy crab, Chinese freshwater crab, Chinese mitten-handed crab, and Chinese mitten crab. The creek crab [may have been] confused with the Chinese mitten crab during translation from the Chinese language to English.)

3. The reproduction and taxonomy between the creek crab and Chinese mitten crab are quite different. The creek crab spends its entire life in freshwater. The female creek crab has her eggs attached to the abdominal region (tail fan). Creek crab eggs range in size from 2.5 to 2.8-mm in diameter, and the total egg number is approximately 50. On the other hand, the size of Chinese mitten crab eggs are about 0.5-mm in diameter, and the total egg number [ranges from] 200,000 to one million. In addition to this difference, the eggs of creek crabs hatch into juvenile crabs, which are similar in appearance to the adult creek crab. However, the Chinese mitten crab is quite different going through larval, zoea, and megalops stages before forming juvenile crabs.

Professor Zhang, Lie-Shi (retired)
Shanghi Fishery Research Institute
Shanghai, China
June 2, 1999

We believe the reason why the lung fluke was reported from mitten crabs is due to English and other foreign language translations of the Chinese. The Chinese people commonly refer to the mitten crab as the "River Crab." In the Chinese language, creek and river are very similar symbols, which probably lead to this misunderstanding.

Although it appears that translation problems may have caused the present confusion, we believe that additional research be done to (1) translate original papers describing the oriental lung fluke; (2) conduct a more thorough analysis of medical records of the geographic range of lung flukes in humans; (3) and to overlay lung fluke distribution on the distribution of mitten crabs and creek crabs. We are confident that once this is done that the mitten crab will be found *not* to be a potential host of lung flukes.

CONTRIBUTED PAPERS

Otolith Sulfur Isotope Method to Reconstruct Chinook Salmon (*Oncorhynchus tshawytscha*) Life History

Peter K. Weber, Ian D. Hutcheon, Kevin D. McKeegan, and B. Lynn Ingram; pweber@socrates.berkeley.edu[1]

Abstract

Here, we report a new ion microprobe method to help reconstruct fish life history based on sulfur isotopes ($^{34}S/^{32}S$, expressed as $\delta^{34}S$). Selected hatchery-raised and naturally-spawned juvenile chinook salmon are shown to have a $12.96 \pm 0.27‰$ (mean $\pm$ 2 SE) difference in muscle $\delta^{34}S$ values, corresponding to $\delta^{34}S$ differences between the hatchery and freshwater diets. Isotopic microanalyses of otoliths demonstrate that this 13‰ difference is preserved in the otoliths. We interpret the otolith $\delta^{34}S$ record to be a chronology of dietary $\delta^{34}S$, with approximately one-week temporal resolution, preserved in these banded calcium carbonate structures. Potential applications include identifying hatchery-raised fish and reconstructing nutrition sources, migration, and other aspects of chinook salmon life history.

Introduction

Sulfur isotopes are useful for the study of nutrient flows and migratory patterns in large part because marine and continental food webs typically have substantially different sulfur isotopic compositions (Peterson and others 1986; Nriagu and others 1991). Bacterial sulfate (SO_4^{2-}) reduction in the oceans enriches marine SO_4^{2-} in ^{34}S relative to sulfur in the earth's crust ($\delta^{34}S$ of +21‰ versus a mean of ~0‰) (Thode 1991). The $\delta^{34}S$ of river water SO_4^{2-} varies regionally between –5‰ and +15‰ according to bedrock lithology, anthropogenic inputs, and atmospheric deposition from natural sources, with a global average value of approximately +7‰ (Nriagu and others 1991). Photosynthetic plants use inorganic sulfur, such as SO_4^{2-}, to synthesize sulfur-bearing compounds with a small amount of isotopic fractionation (0‰ to –3‰ for marine, and –5‰ on average for freshwater plants) (Nriagu and others 1991). The $\delta^{34}S$ signal established by primary producers is maintained in the food web because the essential sulfur-bearing compounds are incorporated into the tissue of consumers without significant fractionation (Peterson and others 1986; Nriagu and others 1991), generating a substantial difference in $\delta^{34}S$ between marine and most continental food webs. Smaller but still useful differences can be found within freshwater systems (Nriagu and others 1991). In fish, $\delta^{34}S$ can readily be determined in muscle and organ samples by standard isotope ratio mass spectrometry techniques, providing time-averaged dietary $\delta^{34}S$ information (Hesslein and others 1993).

We hypothesize that the otolith organic matrix contains a permanent record of a fish's dietary sulfur history. Otoliths are calcium carbonate concretions in the inner ear of bony fish (chinook salmon, in this study) that accrete with daily and seasonal growth increments, preserved by successive growth layers. Sulfur (100 to 600 ppm by weight) is associated with the otolith organic matrix (Kalish 1989). Otolith chemistry has been extensively analyzed (Campana 1999), but no measurements of otolith $\delta^{34}S$ have been reported. We expect the organic matrix in the center of each salmon otolith to reflect the marine sulfur isotopic composition of the mother, transmitted via the egg to the fish. Once the juvenile salmon hatches out and begins to feed, the $\delta^{34}S$ of each otolith growth increment should reflect the diet of the fish at that particular time (that is, the otolith layers preserve a temporal record of fish diet).

We test this hypothesis by making *in situ* measurements of otolith $\delta^{34}S$ for hatchery-raised and naturally-spawned juvenile chinook salmon (*Oncorhynchus tshawytscha*) (Figure 1). Hatchery-raised and naturally-spawned salmon should have distinct juvenile dietary $\delta^{34}S$ histories in most river systems. In the hatchery, juvenile salmon are raised on commercial feeds typically consisting of 80% to 90% protein from marine sources, whereas in the wild, juvenile salmon have a freshwater

1. P.K. Weber, Dept. of Geography, University of California, Berkeley. I.D. Hutcheon, Analytical and Nuclear Chemistry Div., Lawrence Livermore National Laboratory, Livermore, CA. K.D. McKeegan, Dept. of Earth and Space Sciences, University of California, Los Angeles, CA. B.L. Ingram, Dept. of Earth and Planetary Science, University of California, Berkeley, CA.

diet. We analyze tissue and food samples to show that hatchery-raised and naturally-spawned juvenile chinook salmon have distinct dietary sulfur histories. We compare hatchery and source river water dissolved sulfur content to exclude significant additions of exogenous sulfur from hatchery operations (feeding, for example). Finally, we analyze otolith δ^{34}S by ion microprobe, generating a spatially-resolved δ^{34}S record.
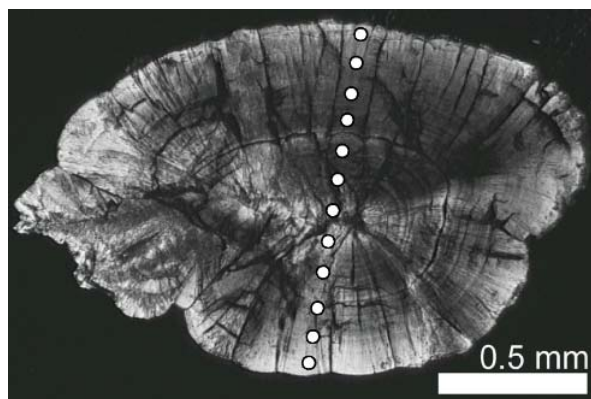
Figure 1   Transmitted light micrograph of a polished otolith from a juvenile chinook salmon showing concentric growth increments and ion microprobe traverse used to determine δ^{34}S. *In situ* ion microprobe analyses reveal variations in δ^{34}S, correlated with radial position (salmon age), that track changes in nutrient source/diet δ^{34}S, which can in turn be related to aspects of salmon life history (Figure 3).

Methods

Five sets of juvenile chinook salmon from the Sacramento-San Joaquin river system were used in this study. One set of fish came from a river with no hatchery stocking (Butte Creek), another set was captured in August in a river that last received hatchery fish four months before (Sacramento River at Red Bluff), the third set was taken directly from a hatchery (Feather River Hatchery), the fourth set consisted of naturally-spawned chinook salmon fry recently emerged from the gravel of the Feather River (34 to 38 mm fork length, FL), and the fifth set contained tagged hatchery-raised salmon (Merced River Hatchery) released in the Tuolumne River and recaptured in the Sacramento-San Joaquin Delta 25 days later. With the exception of the fry, the fish caught in the wild were all larger than 60 mm FL, and the fish taken directly from the hatchery were larger than 45 mm FL.

The Butte Creek, Sacramento River, and Feather River Hatchery fish were used to characterize dietary and resultant bulk muscle tissue δ^{34}S for the naturally-spawned and hatchery-raised juvenile salmon because these fish were expected to be in equilibrium with their diets. Whole prey items were extracted from the stomachs of salmon caught in the wild, three commercial chinook salmon feeds were obtained from the Feather River and Merced River hatcheries, and stomach contents were extracted from three of the hatchery salmon. To characterize pre-feeding salmon δ^{34}S, two sets of chinook salmon eggs and the four naturally-spawned chinook salmon fry were analyzed. All muscle, stomach content, feed and egg samples were dried at 60 °C and ground to a fine powder. Lipids were extracted using methylene chloride and methanol (2:1, v/v). The lipid-extracted samples were analyzed for ^{34}S/^{32}S ratio by an isotope ratio mass spectrometer coupled to an elemental analyzer.

To test for sulfur additions in the Merced River Hatchery, matched pairs of filtered water samples (0.4 mm) were collected from the hatchery raceways and the adjacent river when salmon were present (February 1998, March 1998, and January 1999). Total sulfur was determined by inductively coupled plasma atomic emission spectrometer. Replicate analyses of matched pairs were made using concentrated and spiked aliquots.

We selected otoliths from the Butte Creek juvenile salmon for analysis to characterize otolith δ^{34}S in the wild because these fish were the most likely to be naturally-spawned. Otoliths from the recaptured Merced River Hatchery salmon were selected to characterize otolith δ^{34}S in the hatchery and after release. Otoliths were removed, cleaned in deionized water, dried at 60 °C, mounted in Araldite epoxy, and polished to expose banding (Figure 1).

The spatial distribution of sulfur isotopes in otoliths was determined using an ion microprobe. The ^{34}S/^{32}S ratios were corrected for instrumental mass-dependent fractionation by comparison to analyses of pressed standards composed of 95% calcium carbonate and 5% dried, lipid-extracted fish muscle with known sulfur isotopic compositions. All ^{34}S/^{32}S ratios are expressed as δ^{34}S values, the deviation in per milliliter relative to the Canyon Diablo Troilite (CDT) standard:

$$\delta^{34}S = \left[\frac{(^{34}S/^{32}S)_{\text{sample}}}{(^{34}S/^{32}S)_{\text{CDT}}} - 1\right] \times 1000$$

Measurement uncertainty is presented as two standard errors (2 SE) for all analyses. The sulfur concentration in the otoliths (100 to 500 ppm) was sufficient to measure $\delta^{34}S$ at a single spot to within 1% to 2% (external precision). The temporal resolution of the analyses is limited by the ~20 µm diameter of the primary beam. Juvenile salmon otoliths have 2 to 10 µm daily growth increments and each single spot analysis averages four to eight daily bands in these otoliths. The $\delta^{34}S$ data thus provide a chronology with roughly one-week resolution.

Results and Discussion

Our $\delta^{34}S$ data for eggs and fry (Figure 2) demonstrate that the adult salmon $\delta^{34}S$ signal (+17‰ to +18‰; Krouse and others 1991) is transmitted to the juvenile fish via the egg. With time and growth (>45 mm FL), this signal in the tissue is replaced by the dietary $\delta^{34}S$ value (Figure 2), as expected (Hesslein and others 1993). Our results show a substantial difference in muscle tissue $\delta^{34}S$ (12.96 ± 0.27‰) between juvenile salmon feeding in the hatchery and those feeding in the rivers. This difference is large relative to both sample variability (2 SD of 1.0‰ to 1.8‰) and measurement precision (2 SE of 0.6‰). Wild salmon $\delta^{34}S$ values for muscle (+1.0‰ to +3.8‰) and stomach content (+1.3‰ to +4.5‰) are in the range expected for freshwater sulfur sources. In contrast, the $\delta^{34}S$ values in the muscle tissue of the hatchery-raised fish (+14.6‰ to +16.4‰) are indicative of sulfur derived from the hatchery feeds (+14.1‰ to +16.6‰), reflecting a marine signature modified by the admixture of sulfur from continental sources.
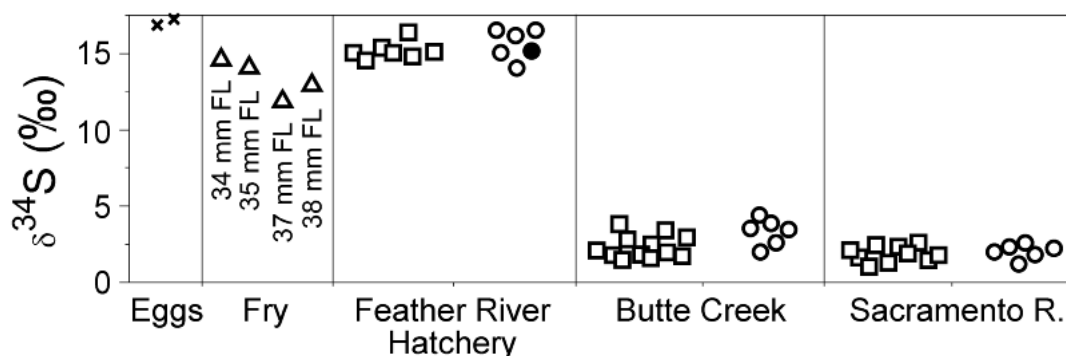
Figure 2 Sulfur isotope composition of muscle tissue (squares) from hatchery-raised (>45 mm fork length) and naturally-spawned juvenile (>60 mm FL) chinook salmon, with comparison to $\delta^{34}S$ of diet (open circles; filled circles for Merced River Hatchery feed), eggs (crosses), and recently-hatched, naturally-spawned fry (triangles). The egg (n = 2) and fry (n = 4) data demonstrate that the maternal marine $\delta^{34}S$ signal is transmitted to the pre-feeding juvenile fish. The data for muscle tissue of the larger juvenile fish (n = 7, 12 and 10, from left to right) show an unambiguous difference in $\delta^{34}S$ (12.96 ± 0.27‰) between hatchery-raised and naturally-spawned fish. The larger fish are in approximate equilibrium with their diets (n = 6, 6 and 6), as expected based on known history and size. Butte Creek salmon are expected to be naturally-spawned in the wild because the river is not stocked with hatchery salmon. The Sacramento River samples were collected at the Red Bluff diversion dam four months after the last releases from the upstream hatchery and, therefore, any hatchery fish still in the river would reflect a freshwater diet in the wild. Data point size represents two standard errors.

Filtered water samples from the Merced River Hatchery and adjacent river contain 0.7 to 1.5 parts per million by weight (ppmw) sulfur. Matched pairs have the same sulfur content within error (mean river-hatchery = 0.03 ± 0.25 ppmw), suggesting hatchery operation does not add significant amounts of exogenous dissolved sulfur to river water diverted to the hatchery raceways. This observation is consistent with strontium isotope and major and minor elemental data for this hatchery and others in the Sacramento-San Joaquin river system, which also suggest hatchery operation does not alter source water chemistry (Weber 2002). If little exogenous sulfur is added to hatchery water, then the hatchery water sulfate $\delta^{34}S$ is not significantly elevated relative to river water sulfate $\delta^{34}S$.

In situ analyses of δ^{34}S in two otoliths from a naturally-spawned juvenile salmon and a recaptured juvenile hatchery-raised salmon are presented in Figure 3. The data show large differences in sulfur isotope composition correlated with nutritional history. For the naturally-spawned fish, the δ^{34}S of the otolith core (14.4 ± 2.2‰, 2 SE, external precision) reflects the marine signal from the egg. The δ^{34}S abruptly decrease to values near zero (−0.4 ± 1.3‰) approximately 150 mm from the center, reflecting growth of the salmon in fresh water. In contrast, the bulk of the otolith from the hatchery-raised salmon (Merced River Hatchery) reflects the marine and hatchery-feed δ^{34}S signal (+12.9 ± 1.5‰). Only the outermost 25 growth bands (about 100 mm wide) of the otolith, formed during the 25 days between release of the salmon and its subsequent capture downstream, have the freshwater δ^{34}S value (−0.6 ± 2.0‰). Pooling the data for the two otoliths, the sulfur isotope composition of the hatchery-feeding and river-feeding zones differs by 13.33 ± 0.97‰ (internal precision).

At our current levels of accuracy and precision, we are unable to distinguish between the marine δ^{34}S signal in the otolith core and the (largely) marine signal derived from the hatchery feed. We are also unable to determine if the offset in otolith δ^{34}S relative to muscle δ^{34}S is an artifact of the mass-fractionation correction, or an actual difference between otolith and muscle δ^{34}S.

Based on the observations that (1) the spatial variation of otolith sulfur content is consistent with the spatial variation in otolith protein content and (2) the sulfur content of an otolith is consistent with the total amount of sulfur in the proteins of the organic matrix, Kalish (1989) inferred that S-bearing amino acids in the organic matrix are the primary source of sulfur in otoliths. Otoliths are 0.2% to 10% protein, containing 1% to 3% cysteine and methionine (Degans and others 1969), which are 26.5% and 21.5% S by weight, respectively (Kalish 1989). However, there is evidence of sulfated acid mucopolysaccharides in otoliths (Asano and Mugiya 1993), and their abundance and provenance have not been studied. Mugiya and Iketsu (1987) demonstrated that inorganic sulfate in ambient water is incorporated into an otolith under experimental conditions, most likely in the organic matrix as sulfated acid mucopolysaccharides. Our sulfur concentration results for matched pairs of water samples exclude hatchery water sulfate as a significant source of elevated δ^{34}S for the otolith hatchery-feeding

zone, supporting the thesis that diet is the primary source of otolith sulfur under river and hatchery conditions.
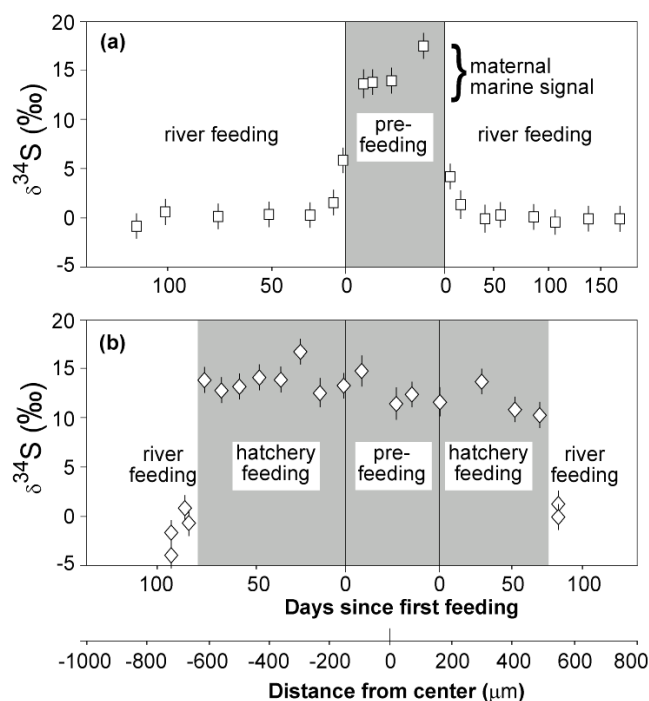
Figure 3 Spatially resolved otolith δ^{34}S values for (a) a juvenile naturally-spawned salmon and (b) a recaptured juvenile hatchery-raised salmon, measured by ion microprobe. The data reveal an unambiguous difference in the distribution of δ^{34}S values across individual otoliths, correlated with salmon diet and life history. See text for full explanation. Error bars represent two standard errors.

Applications

Hatchery managers can use a number of physical, chemical, and thermal methods to mark hatchery fish, but not all hatchery fish are marked. In California's Sacramento-San Joaquin river system, only 10% to 20% of hatchery chinook salmon are marked, primarily because of concerns about physiological stress to the fish and cost (personal communications, see "Notes"). In this river system, otolith δ^{34}S will be useful for identifying hatchery salmon. This method also will work in other systems where (1) fish are released from the hatchery after significant feeding and growth occur, (2) the hatchery feed is marine-based, and (3) exceptionally high δ^{34}S lithologies do not dominate the freshwater δ^{34}S signal (Nriagu and others 1991; Thode 1991). Where hatchery-raised fish can be identified, the timing of the release of fish to the river also can be determined.

More generally, *in situ* analyses of $\delta^{34}S$ can be used to reconstruct aspects of fish life history, given sufficient differences in $\delta^{34}S$ between geographic regions and food sources of interest. The presence of the marine $\delta^{34}S$ value in the center of the otolith can be used to distinguish anadromous from resident populations. Regional differences in river $\delta^{34}S$ (Nriagu and others 1991) should be useful for determining fish origin and reconstructing migration. For estuary or migratory fish, bulk tissue $\delta^{34}S$ provides time-averaged information on nutrition sources (Hesslein and others 1993). By contrast, spatially resolved otolith $\delta^{34}S$ analyses provide a time-resolved record of dietary $\delta^{34}S$.

Acknowledgements

References

Asano M, Mugiya Y. 1993. Biochemical and calcium-binding properties of water-soluble proteins isolated from otoliths of the tilapia, *Orechromis niloticus*. Comp Biochem Physiol B 104:201–5.

Campana SE. 1999. Chemistry and composition of fish otoliths: pathways, mechanisms and applications. Mar Ecol Prog Ser 188:263–97.

Degans ET, Deuser WG, Haedrich RL. 1969. Molecular structure and composition of fish otoliths. Mar Biol 2:105–13.

Hesslein RH, Hallard KA, Ramlal P. 1993. Replacement of sulfur, carbon and nitrogen in tissue of growing broad whitefish (*Coregonus nasus*) in response to a change in diet traced by delta-^{34}S, delta-^{13}C and delta-^{15}N. Can J Fish Aquat Sci 50:2071–6.

Kalish JM. 1989. Otolith microchemistry: validation of the effects of physiology, age and environment on otolith composition. J Exp Mar Biol Ecol.132:151–78.

Krouse HR, Stewart JWB, Grinenko VA. 1991. Pedosphere and biosphere. In: Krouse HR, Grinenko VA, editors. Stable isotopes: natural and anthropogenic sulphur in the environment. New York (NY): J Wiley & Sons. SCOPE 43:267–306.

Mugiya Y, Iketsu H. 1987. Uptake of aspartic acid and sulfate by calcified tissues in goldfish and tilapia. Bull Fac Fish Hokkaido Univ 38:185–90.

Nriagu JO, Rees CE, Mekhtiyeva VL, Lein AY, Fritz P, Drimmie RJ, Pankina RG, Robinson BW, Krouse HR. 1991. Hydrosphere. In: Krouse HR, Grinenko VA, editors. Stable isotopes: natural and anthropogenic sulphur in the environment. New York (NY): J Wiley & Sons. SCOPE 43:177–265.

Peterson BJ, Howarth RW, Garritt RH. 1986. Sulfur and carbon isotopes as tracers of salt-marsh organic matter flow. Ecology 67:865–74.

Thode HG. 1991. Sulfur isotopes in nature and the environment: an overview. In: Krouse HR, Grinenko VA, editors. Stable isotopes: natural and anthropogenic sulphur in the environment. New York (NY): J Wiley & Sons. SCOPE 43:1-26.

Weber PK. 2002. Geochemical markers in the otoliths of chinook salmon in the Sacramento-San Joaquin river system, California [Ph.D. thesis]. Available from University of California, Berkeley.

Notes

Rich Bryant, Mokelumne River Hatchery, Clemments, California.

Mike Cozart, Merced River Hatchery, Snelling, California.

Anna Kastner, Feather River Hatchery, Oroville, California.

John Scott, Coleman Hatchery, Anderson, California.

Terry West, Nimbus Hatchery, Rancho Cordova, California.

Pulsey, Patchy Water Quality in the Delta: Implications for Meaningful Monitoring

Lisa V. Lucas (USGS Menlo Park), Tara S. Schraga (USGS Menlo Park), Cary B. Lopez (USGS Menlo Park), Jon R. Burau (USGS Sacramento), and Alan D. Jassby (UC Davis); lisalucas@usgs.gov

Introduction

Valuable water quality and biological datasets have been gathered in the Sacramento-San Joaquin Delta for decades, most notably by the Interagency Ecological Program's Environmental Monitoring Program (EMP). These extensive data have provided a means of analyzing and detecting long-term trends in water quality and ecosystem function (Jassby and others 2002; Kimmerer and Orsi 1996; Orsi and Mecum 1996) and may shape future restoration actions in the region. EMP water quality data—as well as data generated by the San Francisco Estuary Institute's (SFEI) Regional Monitoring Program (RMP) and research groups like our own—have often focused on single, monthly or seasonal samples taken at several discrete points in space. Although such discrete data often push the practical limits of our equipment and human resources, higher resolution monitoring approaches can reveal limitations (in some cases severe) of these more coarse sampling schemes.

We have fortunately had access to research vessels (USBR's R/V *Compliance*, USGS's R/V *Polaris* and R/V *Turning Tide*, and DWR's R/V *San Carlos*) equipped with continuous flow-through instrumentation for detailed "spatial mapping" of water quality in selected regions of the Delta. In addition, we have conducted a series of studies using new technologies for measuring short time scale changes in water quality at a point in space. These detailed methods of data acquisition have demonstrated that constituents such as chlorophyll *a*, dissolved oxygen, specific conductance, and water

temperature may exhibit substantial variability over spatial scales of hundreds of meters or less ("patchiness") and temporal scales of hours or less ("pulseyness"). We have learned that (1) spatially coarse discrete samples may not represent "typical" conditions in a region, and (2) temporally limited discrete data may significantly misrepresent the average conditions at a point in space.

There are several reasons for fine-scale spatial and temporal variations in Delta water quality, and these reasons may be reduced to two sets of co-operating processes: (1) spatially and temporally variable sources and sinks, and (2) transport (Lucas and others 1999a, 1999b). For example, for phytoplankton biomass (measured as chlorophyll *a*), local sources (like photosynthesis) and sinks (such as respiration, consumption by grazers) vary in space and time as functions of turbidity, water column height, water temperature, surface irradiance, sinking, resuspension, and density of benthic and pelagic grazers. Many of these local sources and sinks vary spatially as functions of bathymetry. Further, they may vary substantially over time scales of hours to years, with the diel light and heating cycles accounting for much of the short time scale variability. Distinct from pure lake or river systems, tidal systems have additional hourly-scale variability in local sources and sinks associated with tidal shallowing and deepening of the water column and consequent tidal fluctuations in water column irradiance and benthic grazing intensity (Lucas and Cloern, forthcoming). External point source loadings (river and stream inputs) may provide additional temporally and spatially varying sources of phytoplankton biomass. Thus, the spatial map of sources and sinks for phytoplankton biomass—like other non-conservative scalars—changes continuously, with significant modes of change associated with time scales of hours to years.

Overlaid on the temporally varying spatial map of sources and sinks, hydrodynamic processes cause transport of scalar quantities like phytoplankton biomass across spatial source-sink gradients. In the Delta, transport is driven by several processes (such as tides, freshwater flow, wind, and density-driven currents) with characteristic time scales of variability ranging from minutes to years. Of particular relevance here, oscillatory tidal advection coupled with complex geometry enhances intermingling of patches from different sources, resulting in dispersion and increased scalar patchiness.

Several different transport pathways can evolve from the Delta's interconnecting network of tidal channels and lakes and contribute to patchiness. For example, differences in physical length between connected (and reconnected) channels can enhance dispersion. Consider water flowing out of a tributary channel (Figure 1) and splitting between long and short receiving channels that have the same flow rate and that reconnect downstream. We assume here that both receiving channels are shorter than the tidal excursion. A scalar patch leaves the tributary channel (Figure 1A) and splits between the receiving channels (Figure 1B). Because one patch has longer to travel than the other, the two patches will be separated once they enter the reconnected main channel (Figure 1C). This is one way in which spatial patchiness can develop.

Differences in tidal current phase between connected channels also can enhance dispersion. Tidal current phase differences between channels may be caused by differential tidal wave propagation (that is, when a wave splits into individual wave fronts traveling independently through separate channels) or by resonance (when the local wavelength approaches one-fourth of the effective channel length). Tidal current phase lags also can be caused by differences between environments in the momentum-friction balance. For example, branched channels of different depths or widths will have different balances between inertia and bottom or sidewall friction (in other words, a deeper or wider channel will be more "inertial," while a shallower or narrower channel will be more "frictional"), resulting in differential tidal phasing. Consider water and a scalar patch flowing out of a tributary channel during ebb tide (Figure 2A) and splitting between large (deep and/or wide) and small (shallow and/ or narrow) receiving channels (Figure 2B). Water in the more frictional, small channel will go slack and "turn around" before the water in the more inertial, large channel (Figure 2C). Therefore, during flood tide, the scalar patch from the smaller receiving channel will return to the tributary main channel earlier than the patch returning from the larger receiving channel, resulting in a spatial separation of the patches after returning to the tributary channel (Figure 2D). Similar to the "tidal trapping" mechanism described by Fischer and others (1979), local tidal current phase differences can be a significant source of dispersion in tidal systems with complex geometries and can enhance scalar patchiness.
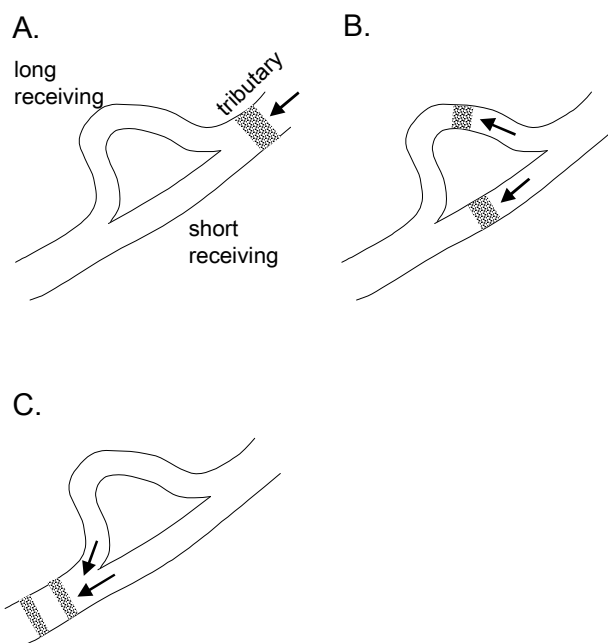
Figure 1 Schematic showing how scalar patchiness can be generated by differences in length of connected and reconnected channels

Tidal trapping, dispersion, and patchiness can be tremendous in the Delta, where the geometry is characterized by extreme connectivity of channels, sloughs, and tidal lakes of varying widths and depths. This setting of complex oscillatory, branching flow and resultant dispersion is further complicated by the temporally varying spatial gradients in local sources and sinks for reactive constituents like those discussed above for phytoplankton biomass. For example, tidal "sloshing" exposes reactive particles to a range of different growth/ consumption environments over time scales of hours (Lucas and others forthcoming, 1999b).

Thus, the combination of spatially variable sources and sinks, tidal advection, and complex geometry may produce extreme patchiness in scalar concentrations, especially if the scalar is reactive (that is, if its sources and sinks depend on its instantaneous local environment). Local temporal variations in sources and sinks contribute to high-frequency variability in scalar concentrations at a fixed point in space. This "pulseyness" may be further enhanced (or at least complicated) by tidal advection of patchy scalar fields past a fixed sampling point.

A. Early ebb   B. Late ebb

C. Early flood   D. Slack after flood
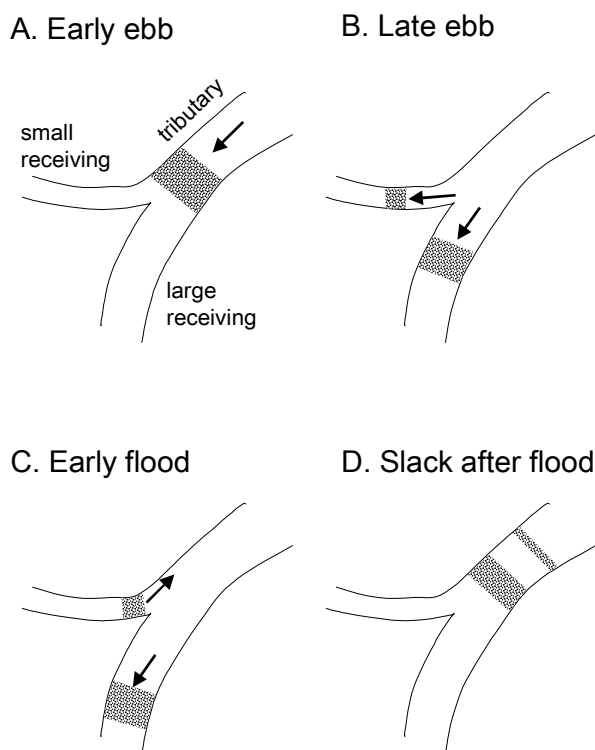
Figure 2 Schematic showing how scalar patchiness can be generated by differential tidal current phasing in a system of connected channels

Here we show two complementary types of measurements (high-resolution spatial maps and high-frequency time series) for two measured quantities (chlorophyll a and dissolved oxygen). These measurements were taken during summer 2001 in the vicinity of Mildred Island (MI), a tidal freshwater lake in the Sacramento-San Joaquin Delta. Other water quality constituents (such as specific conductance and water temperature, not shown) were simultaneously measured and also showed marked patchiness and pulseyness.

Methods

Time series of chlorophyll *a* fluorescence and dissolved oxygen (DO) at a fixed sampling site in southeast MI were obtained, respectively, with a SCUFA (Turner Designs, Inc.) and Hydrolab Datasonde 4 equipped with dissolved oxygen sensor. These moored instruments were deployed in late August 2001, with servicing and discrete sampling for calibration performed approximately weekly for one month. Measurements were obtained and internally logged every 10 minutes (144 measurements/day). Chlorophyll a time series shown are near-surface values, while DO values are near-bottom.
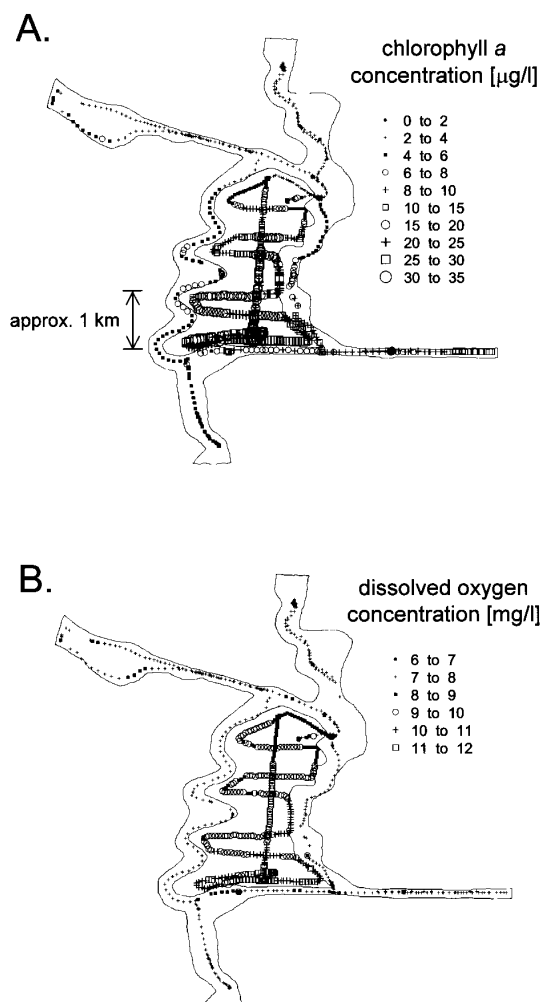
High-resolution spatial mapping of chlorophyll a and DO was accomplished aboard the R/V Turning Tide (inside MI) and R/V San Carlos (in adjacent channels) on 5 September 2001. Ambient water was pumped from approximately 1 m depth and delivered to onboard instruments for continuous measurement of chlorophyll a fluorescence (Turner Designs 10-AU fluorometer) and DO (Seabird YSI on R/V Turning Tide, Beckman probe on R/V San Carlos). Measurements and GPS location were obtained and recorded every 5 seconds. Discrete water samples were collected for determining concentrations of chlorophyll a and DO for instrument calibration. Data from water quality circuits shown here were collected between approximately 2:00 pm and 5:00 pm. For graphical clarity, only every fourth measurement is shown.

Data and Discussion

Patchiness and pulseyness are prominent in our measurements. Figures 3A and B show maps of chlorophyll a and DO, respectively, for MI's interior and adjacent channels. Chlorophyll a ranged from 3-14 mg/l in the channels and 3-33 mg/l in the interior. DO ranged from 6-10 mg/l in the channels and 8-12 mg/l in the interior. Spatial gradients for both chlorophyll a and DO were stronger inside MI than outside; however, patchiness in both constituents—especially in chlorophyll *a*—also is evident in the channels. In many locations, chlorophyll a changed by a factor of 2 or 3 over distances of a few hundred meters or less. Although we are still investigating the mechanisms causing the spatial distributions in Figure 3, previous studies of this region suggest some contributing factors. The strong chlorophyll a gradients inside MI were probably related to slow currents and consequently weak mixing, especially in southern MI, where water residence time has been shown to be relatively long (Lucas and others, forthcoming; Monsen and others, forthcoming). Spatial gradients in local sources and sinks also might have contributed to the interior patchiness. Interior distributions of DO roughly follow the increasing north-to-south gradients in chlorophyll a, possibly due to rapid photosynthesis and slower homogenization by mixing processes in the south (animated hydrodynamic model results will appear at

http://www.esapubs.org/archive/archive_A.htm, Lucas and others, forthcoming). Patchiness in the channels likely results from mechanisms like those discussed above by which tidal advection combines with complex geometry to intermingle different water sources.

A.

chlorophyll *a*
concentration [µg/l]

· 0 to 2
· 2 to 4
· 4 to 6
○ 6 to 8
+ 8 to 10
□ 10 to 15
○ 15 to 20
+ 20 to 25
□ 25 to 30
○ 30 to 35

approx. 1 km

B.

dissolved oxygen
concentration [mg/l]

· 6 to 7
· 7 to 8
· 8 to 9
○ 9 to 10
+ 10 to 11
□ 11 to 12

Figure 3 Measured chlorophyll *a* (A) and dissolved oxygen (B) maps for Mildred Island and neighboring channels on September 5, 2001

Figures 4A and B show 4-day excerpts from our long-term chlorophyll a and DO time series, respectively. A dramatic diel cycle is evident in both records. Chlorophyll a increased and decreased each day by about 10 µg/L (a factor of almost 2), while the amplitude of daily change in DO was about 1-3 mg/l. This is an exceptionally dynamic temporal change at one point in space, and we are currently exploring the biological and physical processes contributing to this strong repeatable pattern.
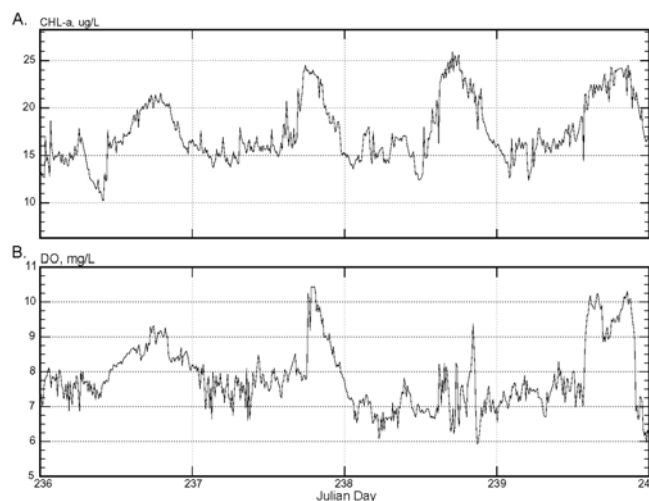
Figure 4 Measured chlorophyll *a* (A) and dissolved oxygen (B) time series for southern Mildred Island during August 2001

Clearly, spatially and temporally limited (discrete) sampling in the MI vicinity during August-September 2001 could have easily yielded misleading information about "typical" conditions within the MI environment. At the southeast time series site, a discrete sampler would have been very lucky to sample at the time of day when chlorophyll a and DO were representative of the daily mean or median. A discrete sampler would have been similarly lucky to sample at a location where chlorophyll *a* and DO were representative of the spatial mean or median. In an environment with so much high-amplitude, fine-scale and high-frequency variability, it is difficult to ascertain the meaning of one discrete sample without prior knowledge of the scales of variability. Moreover, the observed spatial and temporal variations are important system attributes in themselves, and the mechanisms behind that short-scale variability are critical components of large- and long-scale ecosystem function.

The time series in Figure 4 show relatively clear diel cycles, which may make intuitive sense when the diel light and heating cycles are considered (local source/sink processes might be dominant in southern MI). On the other hand, September 2001 chlorophyll *a* time series from other nearby locations display predominant variability that is not on the daily time scale. Therefore, in different locations, even those separated by a remarkably short distance (as is the case in Mildred Island), different processes may govern, resulting in different characteristic

time scales of variability. For example, the dominant time scales may vary with the relative importance of local source/sink processes and transport, and we usually do not know *a priori* the dominant processes or time scales at a location. Further, not all scalar quantities operate on the same time scales, since different processes may govern their dynamics (for example, non-reactive constituents like specific conductance may be less influenced by local sources and sinks than reactive constituents like chlorophyll *a*). Thus, without upfront intensive sampling it may be difficult to know the appropriate time or space scales for monitoring.

Conclusions and Implications

Delta water quality constituents such as chlorophyll *a* and dissolved oxygen may be very patchy in space and pulsey in time. Scalar patchiness may arise from (1) spatial variability in sources and sinks and (2) transport processes causing intermixing of different water sources (such as tidal advection combined with complex geometry). Pulseyness in data records may derive from (1) temporal variability in local sources and sinks and/or (2) advection of distinct scalar patches past a fixed sampling station. Although we may not yet fully understand all the mechanisms shaping patches and pulses observed throughout the Delta, we can—with the appropriate combination of sampling strategies—begin to decipher the Delta's daunting level of variability. Through joint hydrodynamic-scalar measurements and concurrent use of high-frequency time series and high-resolution spatial mapping, the origins of the variability will become more apparent.

This spatial and temporal variability might not be resolved by discrete sampling schemes. Moreover, "typical" (mean, median) concentrations may not be well represented by coarse, infrequent sampling. Even the scales of spatial and temporal variability may vary from location to location—and over time—due to different balances in the processes governing scalar concentrations (for example, the balance between local sources and sinks compared to transport processes). Scales of variability also vary between measured quantities, because different processes govern the variability of different quantities. High frequency variability (refer to the diel oscillations in chlorophyll *a* shown in Figure 4A) may contain important information on the balance of processes governing long-term ecosystem function (that is, short time scale,

periodic, non-linear ecosystem processes can control long-term trends, Lucas and Cloern forthcoming).

Sampling bias and noise are controlled by the way we measure periodic processes. For example, in a location where the diel cycle dominates temporal variability, bias may be decreased by sampling at random times during the day; conversely, noise may be decreased by sampling at the same time of day. Either approach may be appropriate, depending on the goal. If longer-term pattern (such as trends over the spring-neap cycle) is the aim, then same-time-of-day sampling is appropriate; if longer-term average is the aim, then random sampling (at different times of day) is appropriate. These ideas translate to cases where variability occurs predominantly over other (for example, semidiurnal) time scales. If we know a priori that processes are strictly semidiurnal and want to reduce noise, we should try to sample during the same phase of the tide, or roughly an hour later each day. However, if both diel and semidiurnal processes are important, which can be the case for phytoplankton, then only a very complicated and impractical sampling scheme can minimize noise.

Much has been learned from the EMP's discrete sampling program about mechanisms behind the seasonal, interannual, and decadal scales of variability for the estuary. This suggests variability in at least some of the important long-term processes is greater than sampling variability. Observations of large temporal and spatial variability (see Figures 3 and 4), however, do reveal possible sources of sampling noise and suggest we should not expect to explain 100% of the variability seen in the monthly time series. In particular, we expect the problem of signal to noise to be greatest where daily or spring-neap variations are on the order of, or greater than, longer term variability. Detailed, high-frequency measurements in locations of interest (that is, where monthly sampling has been historically conducted) could reveal a great deal about what we can (or cannot) conclude about the long-term trends in existing data sets.

How can we ensure that our sampling schemes yield data representative of a region or time period? First, if dominant scales and amplitudes of variability are not already known, we can perform preliminary high-resolution, high-frequency measurements. Such intensive reconnaissance could yield critical information on the spatial and temporal variability of the quantities of

interest, so that appropriate sampling locations, resolution, times, and frequencies could be incorporated in a less intensive longer-term sampling program (Jassby and others 1997). Second, if a spatial mean or median is of interest, then high-resolution "mapping" of a region can be performed and the mean or median taken from that data pool. Such mapping could be accomplished with flow-through systems like those described above, or by a series of discrete samples which are pooled and then analyzed. Third, if a temporal mean or median is of interest, then high-frequency sampling at a location can be performed and the mean or median taken from that data pool. Such time series can be obtained with instrumentation or with a series of discrete samples which are pooled and then analyzed. Fourth, we can estimate the variance or standard deviation to quantify variability about the spatial or temporal mean and communicate how uniform or constant a measured quantity is.

In addition to extensive discrete sampling, the EMP includes seven continuous monitoring stations (DO is measured at six of these stations, and chlorophyll is measured at four) and is currently proposing to expand its continuous monitoring capabilities. Unfortunately, methods for collecting long-term time series of chlorophyll fluorescence and dissolved oxygen are more resource-intensive than those for conductivity and temperature; therefore, expansion of continuous fluorescence and DO monitoring may lag growth in high frequency measurement of other water quality constituents. Regardless, we see great value in the EMP's movement toward expanded collection and dissemination of high frequency water quality time series.

High-frequency time series could be used in the EMP evaluation process. For example, time series at discrete sampling locations could reveal when and where the EMP's high-slack-tide sampling paradigm is appropriate and where paradigms based on other non-tidal time scales of variability may be more appropriate (that is, in locations behaving like southern Mildred Island). Further, high resolution spatial coverage (as shown in Figure 3, or comparable ongoing monitoring aboard the R/V San Carlos) may be useful in the identification of discrete sampling locations. Fine-scale maps of water quality could help identify regions with lower spatial variability, so that spatially generated noise is minimized in discrete sampling for long-term trends. Such low-gradient locations also may be identifiable through remote sensing.

In general, Bay-Delta projects with monitoring components (for example, monitoring of new or modified habitats in support of CALFED's Ecosystem Restoration Program) should be designed with upfront acknowledgment and preliminary exploration of the space and time scales of variability so that monitoring yields meaningful data.

Acknowledgements

References

Fischer HB, List EJ, Koh RCY, Imberger J, Brooks NH. 1979. Mixing in inland and coastal waters. San Diego (CA): Academic Press. 483 p.

Jassby AD, Cole BE, Cloern JE. 1997. The design of sampling transects for characterizing water quality in estuaries. Est Coast Shelf Sci 45:285–302.

Jassby AD, Cloern JE, Cole BE. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. Limnol Oceanog 47:698–712.

Kimmerer WJ, Orsi JJ. 1996. Changes in the zooplankton of the San Francisco Bay Estuary since the introduction of the clam *Potamocorbula amurensis*. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): Pacific Div AAAS. p 403–24.

Lucas LV, Cloern JE. Forthcoming. Effects of tidal shallowing and deepening on phytoplankton production dynamics: a modeling study. Estuaries.

Lucas LV, Cloern JE, Thompson JK, Monsen NE. Forthcoming. Functional variability of habitats within the Sacramento-San Joaquin Delta: restoration implications. Ecological Applications.

Lucas LV, Koseff JR, Cloern JE, Monismith SG, Thompson JK. 1999a. Processes governing phytoplankton blooms in estuaries. I: The local production-loss balance. Mar Ecol Prog Ser 187:1–15.

Lucas LV, Koseff JR, Monismith SG, Cloern JE, Thompson JK. 1999b. Processes governing phytoplankton blooms in estuaries. II: The role of horizontal transport. Mar Ecol Prog Ser 187:17–30.

Monsen NE, Cloern JE, Lucas LV, Monismith SG. Forthcoming. A comment on the use of flushing time, residence time and age as transport time scales. Limnology and Oceanography.

Orsi JJ, Mecum WL. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis*, the opossum shrimp, in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): Pacific Div, AAAS. p 375–401.

Zooplankton Production in Shallow Water and Channel Habitats: An Example from Mildred Island

James J. Orsi (DFG), jjorsi@aol.com

Introduction

Because shallow water is considered to be productive fish habitat, its restoration is a primary goal of CALFED (CALFED 2000). In 2001, the U.S. Geological Survey (USGS) studied phytoplankton production in shallow water habitat at Mildred Island (MI), a flooded farming island with a mean depth of about 5 m in the Delta, (Figure 1). The USGS study (Lucas and others forthcoming) was designed to understand phytoplankton sources, sinks, and distribution within and around MI.

Using USGS samples, this article will examine how habitat type (channel or shallow water) and chlorophyll *a* concentrations affected zooplankton abundance at MI.
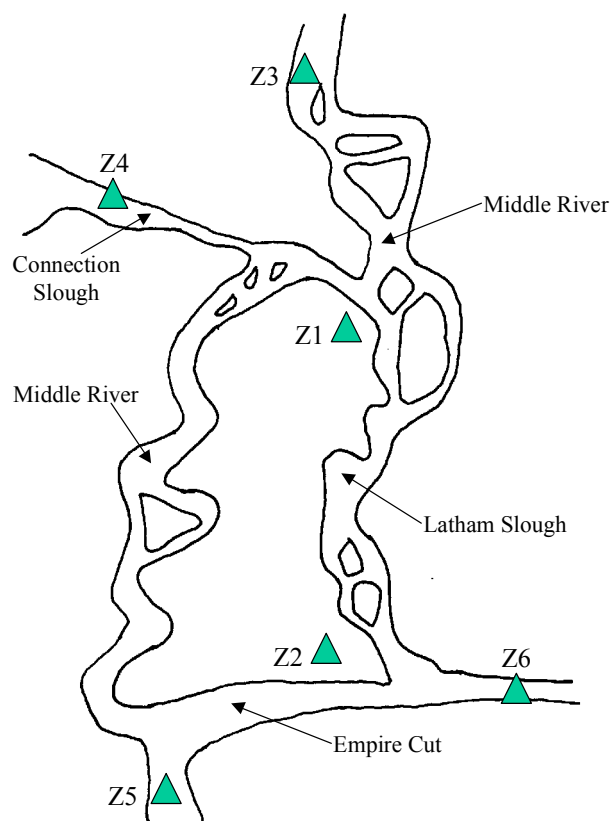
Figure 1 Map of Mildred Island showing sampling stations Z1 through Z6

One hypothesis to be tested is that cladoceran and herbivorous rotifer abundance would be positively correlated with phytoplankton food supply and hence with chlorophyll concentrations. A second hypothesis is that abundance of all taxa would be higher inside MI than in the channels because zooplankton abundance is typically inversely related to the net rate of water movement, which should be lower inside MI. But MI is "leaky"—several breaches enable water to move into and out of the island (Lucas and others forthcoming). The northern half of the island (station Z1) is more tidally energetic due to a large deep opening, whereas the southern half of the island (station Z2) has smaller breaches and hence, less communication with the channels. The difference between the northern and southern parts of MI leads to another hypothesis—that all zooplankton taxa and chlorophyll would be more abundant in southern MI than in the northern part.

Because abundance of the introduced copepods *Pseudodiaptomus forbesi* and *Limnoithona tetraspina* has not correlated with chlorophyll in the Department of Fish and Game (DFG) zooplankton monitoring study (unpublished data) it was not expected to do so at MI. The other copepods taken (*Eurytemora affinis*, *Sinocalanus doerrii*, and *Acanthocyclops vernalis*) were not abundant enough to test against chlorophyll.

Methods

Zooplankton was sampled at six sites, two inside MI (Z1 and Z2) and four in the channels around it (Z3 to Z6), on five sampling dates at weekly intervals from August 23 to September 20, 2001 (Figure 1). Sampling gear consisted of a 0.5-m net with 50-µm mesh and a flow meter in the mouth. One vertical haul was made from bottom to surface at each site and the samples were preserved in 5% formaldehyde in 1-liter jars. Water samples for chlorophyll *a* were usually taken from surface and bottom at the same time as the zooplankton samples and were screened through 100-µm mesh, except on Sept. 5 and 6, when sampling was done at each site at the approximate time of slack tide for two full tidal cycles and surface chlorophyll was measured by fluorometer. Because of the absence of bottom samples on some dates, surface screened values or fluorometer values were used in all analyses.

Zooplankton samples were processed by filtering the jar contents through 43-µm mesh to remove most of the formaldehyde. The material retained on the 43-µm screen was washed into a 1-liter beaker and varying water volumes, depending on zooplankton density, were added to dilute the sample. The contents of the 1-liter beaker were stirred vigorously in a figure-eight pattern to suspend the zooplankton and a 1-ml subsample was withdrawn with an automatic pipette. The subsample was placed on a 1-ml Sedgewick-Rafter counting slide. Usually, only one subsample was examined, but if no adult calanoid copepods were seen, up to three subsamples were scanned for them. Adult copepods were identified to species. Cladocerans were identified to genus except for *Diaphanosoma brachyurum* and *Bosmina longirostris*. The first 50 rotifers on a slide were identified to genus and the rest were counted. The percent breakdown of the 50 identified rotifers was applied to the counts to separate herbivorous and predacious rotifers. The genera *Asplanchna*, *Trichocerca*, and *Synchaeta* were

considered predacious, although the latter two may actually be omnivores. Numbers per cubic meter were calculated from the raw counts, the water volume sampled at a station, and the sample volume in the beaker. The equation was $N = rB/V$, where N is the number per cubic meter, r is the raw count, B is the beaker volume, and V is the water volume sampled.

Analyses of variance were run with herbivorous rotifers, *P. forbesi*, *L. tetraspina*, and cladocerans as the dependent variables and chlorophyll as the independent one. All analyses were run on log transformed data to which 1 had been added, $\log_{10}(Z+1)$, where Z is the number per cubic meter. One was added because the $\log_{10}$ of 0 does not exist.

Results and Discussion

Chlorophyll concentrations were highest at station Z2 in southern MI where a peak of 31.6 µg/L was recorded and second highest at station Z6 in Empire Cut, which usually had concentrations of 7 to 9 µg/L and a peak of 13.3 µg/L (Figure 2). Empire Cut receives water from the Stockton area of the San Joaquin River where chlorophyll concentrations are often moderately high. Chlorophyll concentrations in northern MI (station Z1) were low, 2 to 6 µg/L, and were similar to those in the channels except for Empire Cut. This suggests that due to the large levee breaches, water residence times in northern MI were too short for phytoplankton biomass to build up.

On all sampling dates herbivorous rotifer abundance was considerably higher in MI (mean of stations Z1 and Z2) compared to the channels (Figure 3). Rotifer means inside MI ranged from 22,118 m^{-3} to 112,889 m^{-3} (the latter number came from only Z1 as the Z2 sample was not usable on one date) compared to 7898 m^{-3} to 44,552 m^{-3} in the channels. However, cladocerans, *P. forbesi*, and *L. tetraspina* were sometimes higher in the channels than in MI (Figures 4, 5, and 6).
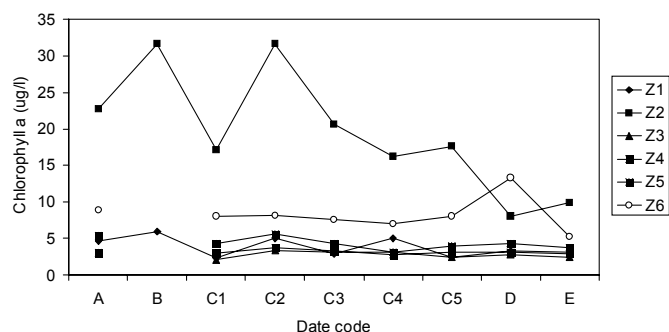
Figure 2 Chlorophyll *a* comparisons and trends at Mildred Island sampling stations from 8/23/01 to 9/20/01. Stations Z1 and Z2 are inside Mildred Island. The others are channel stations. Date codes are A = 8/23, C1 to C5 = 9/5–9/6, D = 9/13, E = 9/20. Stations Z3 to Z6 were not sampled on 8/30.
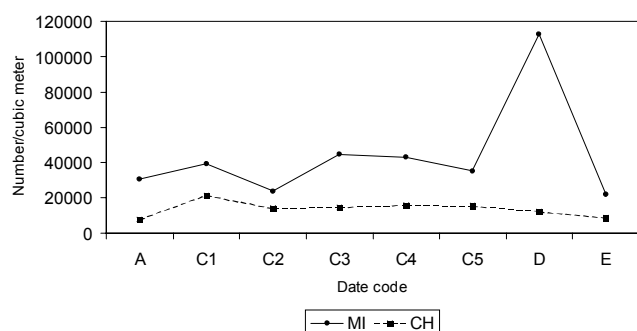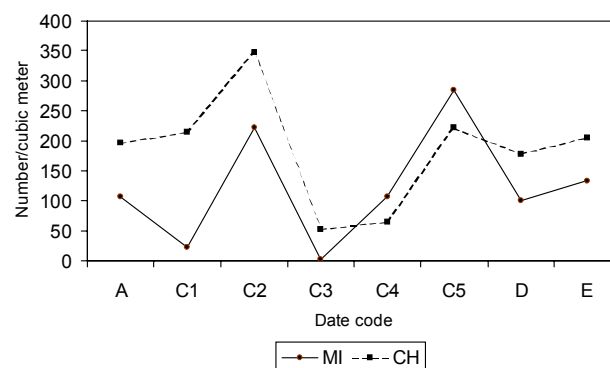

Figure 3 Mean rotifer abundance inside Mildred Island (MI) and in adjacent channels (CH). Date codes as in Figure 2.
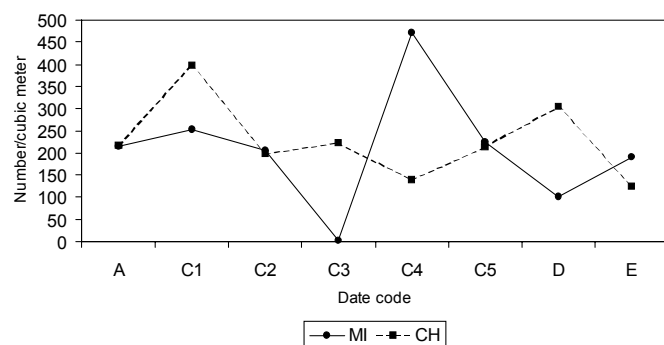
Figure 4 Mean cladoceran abundance inside Mildred Island (MI) and in adjacent channels (CH). Date codes as in Figure 2.
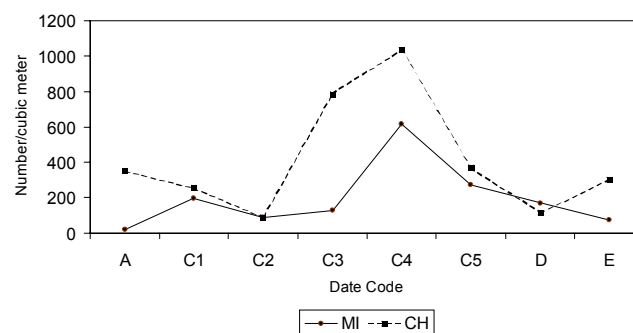

Figure 5 Mean *Pseudodiaptomus forbesi* abundance inside Mildred Island (MI) and in adjacent channels (CH). Date codes as in Figure 2.

Figure 6 Mean *Limnoithona tetraspina* abundance inside Mildred Island (MI) and in adjacent channels (CH). Date codes as in Figure 2.

Only herbivorous rotifers were significantly and positively correlated with chlorophyll ($r = 0.721$, $P > 0.001$) (Figures 7 through 10). However, the highest rotifer abundance, 112,000 m^{-3} was found at a low chlorophyll concentration (3.3 μg/l) in northern MI on 9/20/02 (Figure 11). This point was excluded from the analysis. The rotifer-chlorophyll relationship is actually non-linear as abundance declined at the highest chlorophyll concentrations at Z2. This may be due to the presence at Z2 of filamentous or chain-forming algae, which rotifers do not consume. In April 2000, chain-forming diatoms (*Skeletonema*) accounted for much of the chlorophyll in southern MI (Mueller-Solger, personal communication, see "Notes") and *Skeletonema* also may have been abundant at that location in 2001.
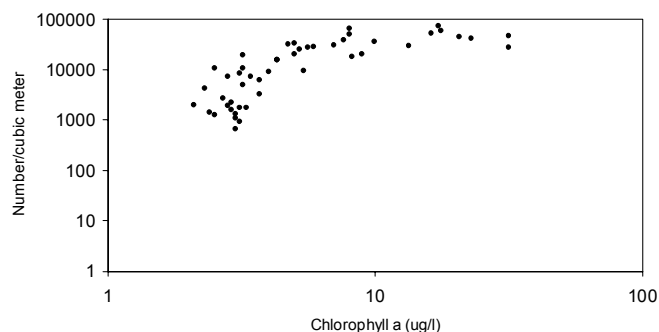
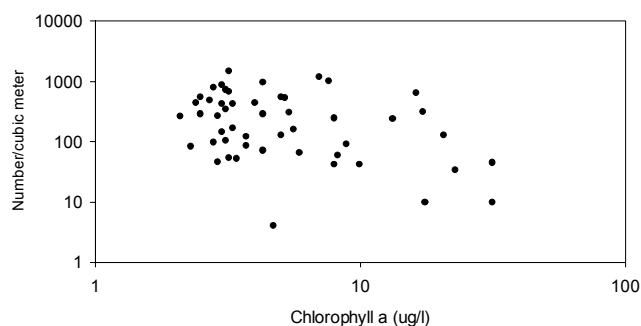**Figure 7 Rotifer abundance vs. screened chlorophyll *a* concentrations at all Mildred Island sampling stations, 8/23–9/20/01**

The abundance of *P. forbesi* was negatively correlated with chlorophyll ($r = –0.441$, $P > 0.001$) and cladocerans and *L. tetraspina* did not correlate significantly with chlorophyll (Figures 8, 9, and 10). Rotifers were consistently more abundant in southern MI, but cladocerans and both copepod species were actually a little less abundant in southern MI than in northern MI (Figures 11, 12, 13, and 14), in spite of the higher chlorophyll in the south and the more lake-like conditions there. The feeding habits of *P. forbesi* are unknown but would be expected to be typical of calanoid copepods, which are omnivores that feed heavily on phytoplankton. *Limnoithona tetraspina* is likely to feed on small motile prey—autotrophic and heterotrophic flagellates and ciliates. Cladocerans are strong herbivores and should have reacted positively to the higher chlorophyll concentrations at Z2 but did not. Again this may be due to chain-forming diatoms. A. Mueller-Solger found that *Daphnia magna* became entangled in *Skeletonema* chains from southern MI samples, but was able to feed efficiently on seston in northern MI samples (personal communication, see "Notes").
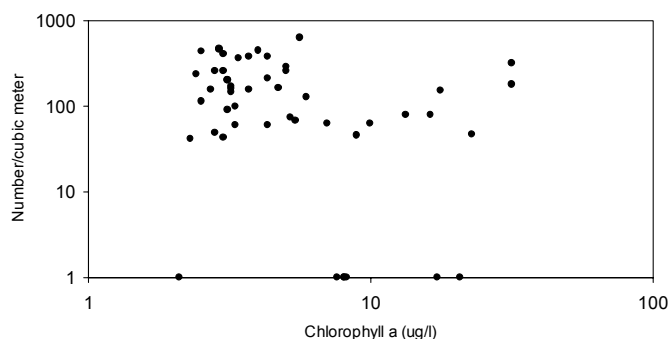
Figure 8 *Pseudodiaptomus forbesi* abundance vs. screened chlorophyll *a* concentrations at all Mildred Island sampling stations, 8/23–9/20/01

Figure 9 Cladoceran abundance vs. screened chlorophyll *a* concentrations at all Mildred Island sampling stations, 8/23–9/20/01
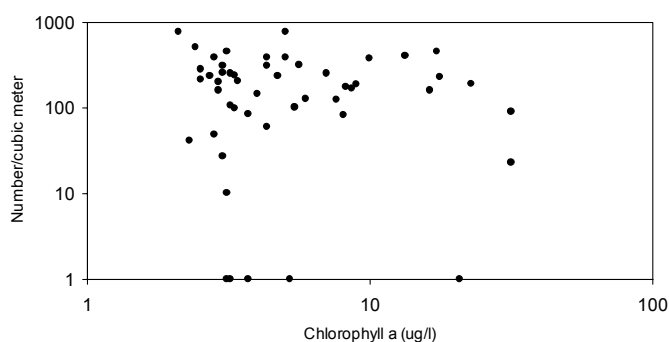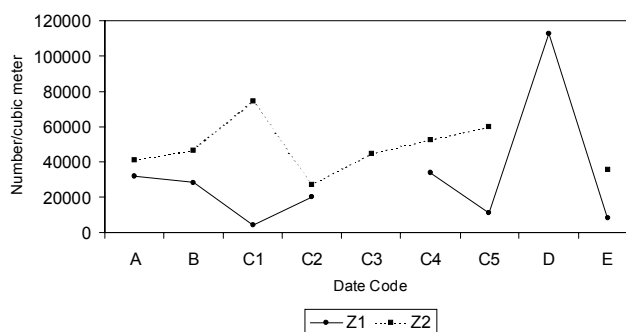

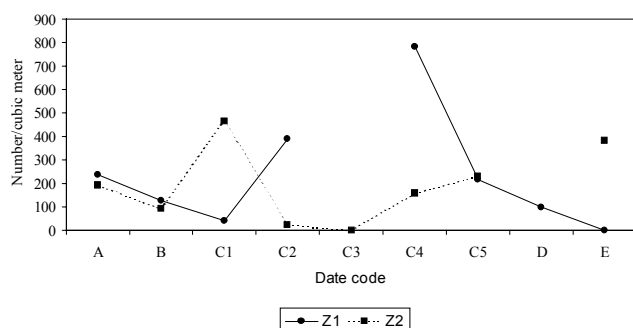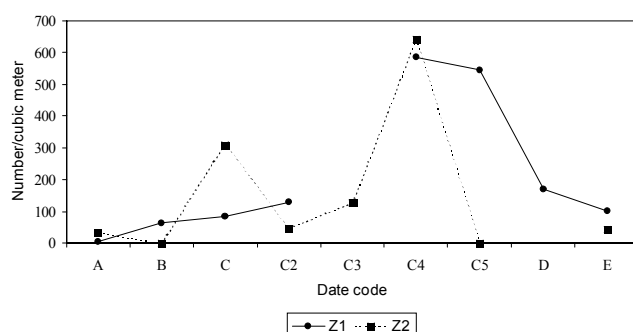**Figure 10 *Limnoithona tetraspina* abundance vs. screened chlorophyll *a* concentrations at all Mildred Island sampling stations, 8/23–9/20/01**


Figure 11 Herbivorous rotifer abundance in northern MI (Z1) compared to southern MI (Z2) on each sampling date. Date code: A = 8/23, B = 8/30, C1–C5 = 9/5–9/6, D = 9/20. Missing C3 and D samples could not be processed because of mud.

Figure 12 Abundance of all cladocerans at stations Z1 (north MI) and Z2 (south MI). Date codes as in Figure 11.

Figure 13 Abundance of *Pseudodiaptomus forbesi* adults at stations Z1 (north MI) and Z2 (south MI). Date codes as in Figure 11.
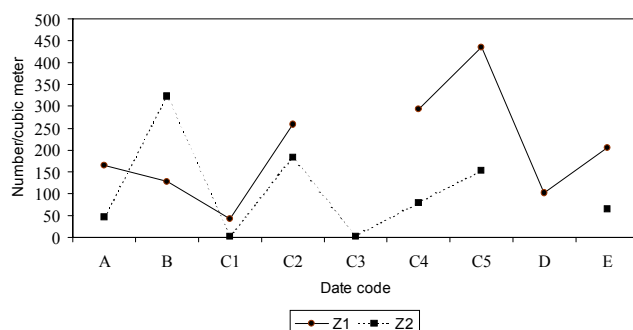
Figure 14 Abundance of *Limnoithona tetraspina* adults at stations Z1 (north MI) and Z2 (south MI). Date codes as in Figure 11.

Water origin may have played a role in chlorophyll concentrations and zooplankton abundance. Although Mildred Island is in the path of cross-Delta flow moving down Old River to the export pumps, some of the water at Empire Cut (Z6) may have originated via Turner Cut from the Stockton area of the San Joaquin River where chlorophyll concentrations and rotifer abundance are usually higher than in the cross-Delta flow. *Limnoithona tetraspina* abundance was low at Z6, probably because it peaks in brackish water and is not abundant at Stockton (DFG data).

Benthic grazing can reduce phytoplankton and either directly (predation on early life stages) or indirectly (through competition for phytoplankton) reduce zooplankton abundance (Kimmerer and others 1984). A USGS study (Lucas and others, forthcoming) of another flooded island, Franks Tract, showed that a dense *Corbicula fluminea* population grazed down the chlorophyll concentrations there. In Mildred Island, *Corbicula* densities were low, especially in southern Mildred Island, and chlorophyll was higher (Lucas and others forthcoming).

Since the rate of tidal interchange can regulate phytoplankton and zooplankton abundance in shallow water habitat, the number, size, and location of breaches in flooded islands will undoubtedly prove to be extremely important to the creation of good fish habitat in such islands. Communication must exist between the interior of islands and adjacent channels so that both fish and zooplankton can move in and out. But excessive communication or flow-through will reduce water residence time and hence may limit phytoplankton and zooplankton production in the islands. Recently, Oltmann and Burau found strong tidal currents moving across Sherman Lake (CALFED 2001). These currents would explain why zooplankton abundance in Sherman Lake has usually been similar to that in the river channels around it (DFG, unpublished data). While it will be possible to control the number and location of breaches around flooded islands, controlling the benthos, principally *Corbicula*, is another matter. We need to know why *Corbicula* is rare in Mildred Island but abundant in Franks Tract.

The data from this study presented here show that shallow water habitat will not necessarily produce higher copepod abundance than deep channels. It may produce more rotifers, which are less affected by water residence time because of their short egg development times, but rotifers are not important fish foods—copepods and cladocerans are. Creation of productive shallow water habitat is as much an art as a science at this stage in our understanding.

The number, depth, width, and location of levee breaches will have large effects on whether shallow water habitat will be a net importer or exporter of phytoplankton and zooplankton. Also important is the density of clams—*Corbicula* in fresh water and *Potamocorbula* in brackish water—and the grazing/predation pressure they exert on both phytoplankton and zooplankton.

Since this study was not designed to answer the basic question of zooplankton productivity in shallow water, we may question if the sampling was adequate to provide meaningful data to answer it. Specifically, was the sampling period long enough and was sampling intensive enough in time and space? Spatial sampling might have been better if sites had been located both near and far from levee breaches inside Mildred Island to shed light on the effects of water interchange on chlorophyll and zooplankton concentrations. Temporal sampling intensity appears adequate—more frequent than weekly sampling would not be expected to provide data differing greatly from what was obtained. However, a study period longer than one month might smooth out the zooplankton-chlorophyll relationships by minimizing short-term effects. For instance, if chain-forming diatoms were not consistently abundant for long periods of time, we would have had a chance to see how zooplankton react when they are not dominant. However, the largest problem with the data is that we lack a comparison site with different characteristics in terms of benthos, phytoplankton composition, and levee breaches. A three-month study at Franks Tract and Mildred Island that sampled benthos, phytoplankton composition, chlorophyll, and zooplankton might have been better able to answer basic questions about zooplankton abundance in shallow water versus deep channel habitats.

Acknowledgments

I thank Jim Cloern (USGS) for permission to use the data, Fred Feyrer (DWR) for comments on the manuscript, Lisa Lucas (USGS) for comments and information, and Sally Skelton (DFG) for technical help.

References

CALFED. 2000. California's water future: a framework for action. Sacramento (CA): CALFED Bay-Delta Program.

CALFED Bay-Delta Program. 2001. Hydrodynamics: a river runs through it. Science in action. News from the CALFED Bay-Delta Science Program December 2001:11.

Kimmerer WJ, Gartside E, Orsi JJ. 1994. Predation by an introduced clam as the probable cause of zooplankton declines in San Francisco Bay. Mar Ecol Prog Ser 113:81–93.

Lucas L, Cloern JE, Thompson JK, Monsen NE. Functional variability of shallow tidal habitats in the Sacramento-San Joaquin Delta: restoration implications. Ecological Applications. Forthcoming.

Lucas L, Schraga T, Lopez C, Burau J, Jassby A. Pulsey, patchy water quality in the Delta: implications for meaningful monitoring. IEP Newsletter [this issue].

Notes

Modifications to an Agricultural Water Diversion to Permit Fish Entrainment Sampling

Zoltan Matica and Matt Nobriga (DWR), zoltan@water.ca.gov

Water diversions in California's Sacramento-San Joaquin Delta can pose a substantial hazard to aquatic fauna (Hallock and van Woert 1959, Arthur and others 1996). The largest water diversions in the Delta are the federal facility at Tracy, the state facility at Clifton Court and the Mirant Corporation power plants in Antioch and Pittsburg. Cumulatively, these facilities can divert more than 60% of the total Delta inflow and are equipped with fish barriers of varying efficiency (Brown and others 1996). Additionally, approximately 2,200 smaller agricultural diversions in the Delta remove an average of about 27% of June–July inflows (White and Kawasaki 1998). Many of these agricultural diversions are located within the boundaries of critical habitat for listed species (DFG 2000) such as delta smelt (*Hypomesus transpacificus*) (USFWS 1993), steelhead (*Oncorhynchus mykiss*) and winter-run chinook salmon (*O. tshawytscha*) (NMFS 2000). Most of these smaller diversions are

unscreened siphons, 30 to 60 cm in diameter, and draw water 60 to 90 cm above the channel bottom.

Unfortunately, little data are available on the effects of small diversions on fish in the Delta. A major limitation is that most conventional sampling gear is designed to work in open water areas and is not effective for use at high velocity agricultural diversions. Another problem is that it is hard to evaluate the potential benefits of adding fish screens; while there are some data on fish entrainment rates through unscreened diversions, it is unclear how many fish might have been saved if a screen had been in place. Here, we report on structural modifications at the outlets of the California Department of Water Resources' (DWR) agricultural diversion facility located in Horseshoe Bend on the lower Sacramento River. Using siphons, the facility diverts river water over the levee for irrigation typically from April through July. This facility had attributes of (1) efficient sampling, allowing 100% of the diverted water to be filtered by nets; (2) adjacent screened and unscreened pipes, allowing evaluation of the benefits of screening; and (3) structural modifications to facilitate future studies.

To comply with requirements of the U.S. Army Corps 404 Permit and a U.S. Fish and Wildlife Service Biological Opinion, the facility was rebuilt in 1997 with two screened pipes, an unscreened pipe, and structural modifications to facilitate future studies of delta smelt entrainment. This was done as part of DWR's mitigation obligations for the construction of the South Delta Temporary Barriers.

The facility consists of an intake structure on the river side and an outlet structure on the inland side at the base of the levee. The intake structure supports a screen backwash pump; flow control valves; two, screened 61-cm pipes; and one, unscreened 61-cm pipe that is modified to accept a future fish screen. This unscreened siphon is in line with the nearest fish screen but 2.3 meters downstream of it. The unscreened siphon is only used during fish entrainment sampling or when there are mechanical problems with the screened siphons. The screened pipes are joined at an intake manifold equipped with two cylindrical fish screens manufactured by Custom Technologies Company, Inc.[1] The screens are 1.5 m long,

---

1. Use of trade names does not imply endorsement by the California Department of Water Resources or by the California Department of Fish and Game.

have a radius of 1.0 m, and made of 2.4-mm woven wire mesh. The centerline of the intake is 1.5 m below the mean low water mark and the screens are 0.6 to 0.9 m off the bottom. Maximum approach velocity at the screens is 6 cm/s (about 0.2 ft/s) when both screened pipes are operated at their theoretical maximum flow of 0.42 m^3/s (per pipe).

The following describes modifications to the Horseshoe Bend facility outlet structure to support fish entrainment sampling. Access over the 0.2 ha outlet pool to the screened and unscreened siphon outlets was provided by a catwalk and a sampling platform (Figure 1). Nets can be attached to each of the two vertical sliding gates by couplers. One sliding gate positions a net over the unscreened outlet and the other positions a second net over the screened outlet. The gates are raised or lowered into place by hand winches. The volume of water sampled can be estimated using propeller flow meters suspended by steel studs in the center of each sliding gate neck.

The custom designed plankton nets (Figure 2) have mouths modified with canvas collars to encompass 3-point coupling rings. The rings connect with pins to the 61-cm diameter necks protruding from the sliding gates. The 1600-μm mesh plankton nets are 5.2 m long, 1.8 m in greatest diameter, and have removable PVC cod-ends. Each net has two aluminum spreader hoops; one 1.8-m diameter hoop 2.1 m from the mouth and one 1.1-m diameter hoop 3.4 m from the mouth. The cod-end is a removable PVC collection tube 0.4 m long with a 0.2 m diameter and has 1600-μm mesh covered openings on its sides. Each hoop and cod-end has bullet floats attached to properly align the nets during sampling. A tender line is attached to the tops of each hoop and the cod-end to facilitate retrieval.

The outlet sampling structure has been in place for four years with no operational problems, even though the intake fish screens have malfunctioned in three of the last four years. DWR conducted fish entrainment sampling during the summer of 2000 and 2001 (Table 1) and demonstrated the effectiveness of the sampling devices by collecting a total of 11,729 fish representing 24 different species. It should be noted that the Horseshoe Bend site is somewhat unique among Delta agricultural diversion facilities, in that it is owned by DWR. In contrast, most facilities are privately owned and operated. Therefore, construction of similar facilities and subsequent sampling

at other locations will require cooperation of landowners or leaseholders.

Table 1 Fish species and numbers collected from sampling of diversion siphons (screened and unscreened combined) at Horseshoe Bend July 12-14, 2000 and July 9-11, 2001

Common name	Latin name	Origin[c]	2000[a]	2001[a]
Threadfin shad	*Dorosoma petenense*	I	60	7,841
Shimofuri goby	*Tridentiger bifasciatus*	I	452	1,628[b]
Yellowfin goby	*Acanthogobius flavimanus*	I	333	381[b]
Striped bass	*Morone saxatilis*	I	302	118
Rainwater killifish	*Lucania parva*	I	10	168
Inland silverside	*Menidia beryllina*	I	0	160
White catfish	*Ameiurus catus*	I	32	70
Channel catfish	*Ictalurus punctatus*	I	6	55
Delta smelt	*Hypomesus transpacificus*	N	12	31
Largemouth bass	*Micropterus salmoides*	I	2	12
Lamprey	*Lampetra* spp.	N	3	8
Tule perch	*Hysterocarpus traski*	N	10	0
American shad	*Alosa sapidissima*	I	7	2
Black crappie	*Pomoxis nigromaculatus*	I	4	4
Bluegill	*Lepomis macrochirus*	I	0	4
Prickly sculpin	*Cottus asper*	N	3	1
Goldfish	*Carassius auratus*	I	2	0
Starry flounder	*Platichthys stellatus*	N	2	0
Black bullhead	*Ameiurus melas*	I	0	1
Bigscale logperch	*Percina macrolepida*	I	1	0
Brown bullhead	*Ameiurus nebulosus*	I	0	1
Sacramento blackfish	*Orthodon microlepidotus*	N	1	0
Sacramento sucker	*Catostomus occidentalis*	N	0	1
Splittail	*Pogonichthys macrolepidotus*	N	1	0

[a]During each of these sampling periods, < 1.5% of the fish collected were from the screened siphon.

[b]Numbers are those reported by California Department of Fish and Game lab staff. Some identifications were determined to be incorrect based on length frequency distributions and comparisons among samples identified by different persons.
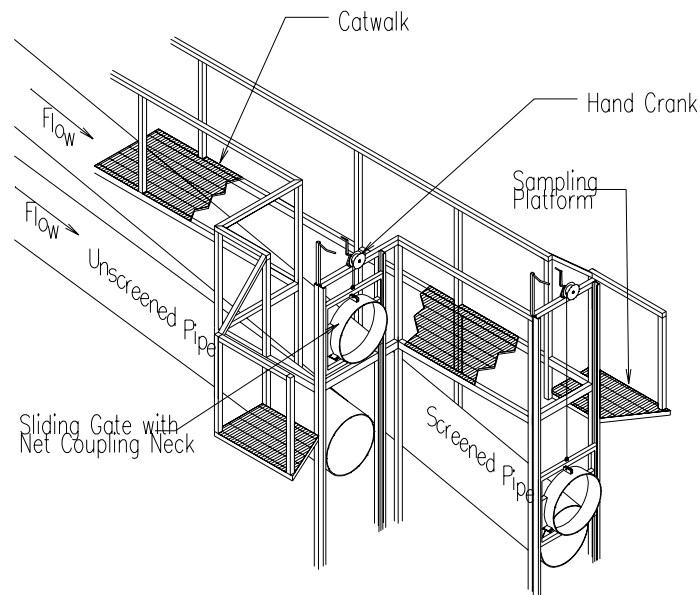
Figure 1 Sampling structure with net coupling sliding gates for a screened and unscreened pipe (R. Beckwith)
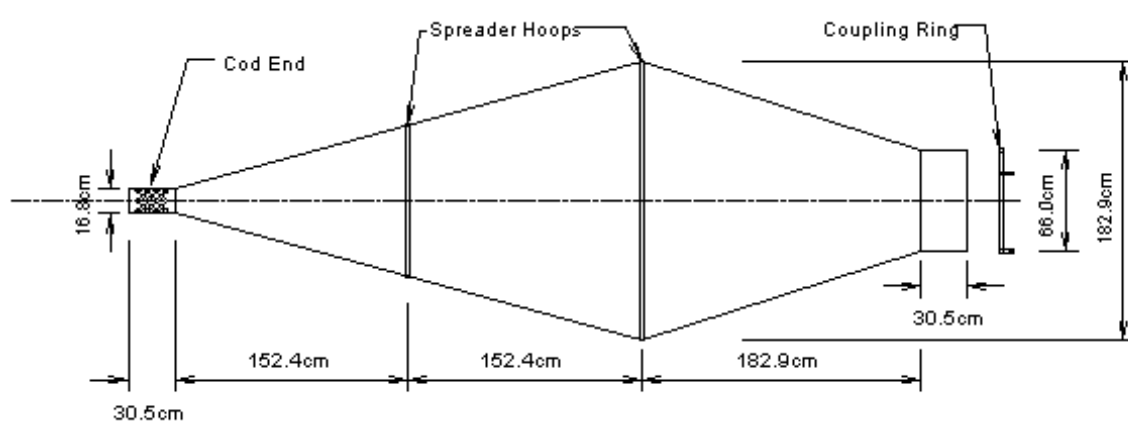
Figure 2 Modified fyke net with 2 spreader hoops and a coupling ring (R. Beckwith)

References

Arthur JF, Ball MD, Baughman SY. 1996. Summary of federal and state water project environmental impacts in the San Francisco Bay-Delta Estuary, California. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): Pacific Div AAAS. p 445–96.

Brown R, Greene S, Coulston P, Barrow S. 1996. An evaluation of the effectiveness of fish salvage operations at the intake to the California Aqueduct, 1979–1993. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): Pacific Div AAAS. p 497–518.

[DFG] California Department of Fish and Game. 2000 April. State and federally listed endangered and threatened animals of California. April 2000 [web page]. Available from: http://www.dfg.ca.gov/endangered/t_e_animal.pdf, via the INTERNET. Accessed 2000 December.

Hallock RJ, van Woert WF. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. California Fish and Game 45(4):227–96.

Herren JR, Kawasaki SS. 2001. Inventory of water diversions in four geographic areas in California's Central Valley. In: Brown RL, editor. Fish Bulletin 179. Contributions to the biology of Central Valley salmonids, volume 2. Sacramento (CA): California Department of Fish and Game. p 343–55.

[NMFS] National Marine Fisheries Service. 2000. Designated critical habitat: Critical habitat for 19 evolutionary significant units of salmon and steelhead in Washington, Oregon, Idaho, and California. Federal Register 16 February 2000 (50 CFR 226).

[USFWS] U.S. Fish and Wildlife Service. 1993. Final rule listing the delta smelt as a threatened species. Federal Register 5 March 1993 (58 FR 12854).

White JR, Kawasaki SS. 1998. Inventory of water diversions in four geographic areas in California [draft]. California Department of Fish and Game, Sacramento, California.

Assessing Fish Entrainment Vulnerability to Agricultural Irrigation Diversions: A Comparison Among Native and Non-Native Species

Matt Nobriga (DWR), Zoltan Matica (DWR), and Zach Hymanson (CALFED), mnobriga@water.ca.gov

Introduction

Humans divert water from aquatic ecosystems for numerous reasons, and not surprisingly, water diversion is often considered a major stressor of aquatic resources (Dadswell and Rulifson 1994; Kingsford 2000). The Sacramento-San Joaquin Delta is no exception. Aquatic ecosystem impacts attributable to State Water Project (SWP) and federal Central Valley Project (CVP) operations have been reported previously (Jassby and others 1995; Arthur and others 1996; Bennett and Moyle 1996). In addition to SWP and CVP diversions, crops grown within the Delta are irrigated using water directly withdrawn from adjacent channels via more than 2,200 diversions distributed throughout the system (Herren and Kawasaki 2001). All of these irrigation diversions are shore based, most are small (30- to 60-cm pipe diameter); they operate via pumps or gravity flow and lack fish screens. Like the SWP and CVP diversions, fish losses to Delta irrigation diversions have been a concern for many years (Hallock and van Woert 1959).

Based on the large number of irrigation diversions, CALFED (2000) considered retrofitting many or all with fish screens as a component of a comprehensive restoration strategy. Fish screens may benefit the threatened delta smelt, *Hypomesus transpacificus*. Delta smelt have been reported from samples of Delta irrigation diversions (Hallock and van Woert 1959; Spaar 1994; Cook and Buffaloe 1998) as well as larger wetland management diversions downstream (Pickard and others

1982). However, fish screens also may pose hazards for delta smelt. Under laboratory conditions, delta smelt contact with a fish screen increased with increasing resultant flow velocities near the screen face (Swanson and others 2002). Screen contact resulted in anything from increased stress response to death, depending on its frequency and severity.

In addition, delta smelt were found to have more contact with fish screens at night (Swanson and others forthcoming). Delta smelt primarily occur in large open water habitats (Sweetnam 1999), but distribution is influenced by tidal and diel cycles (Aasen 1999; Bennett and others 2002), which could affect vulnerability to shore-based diversions. Recent studies of Delta irrigation diversions (Spaar 1994; Cook and Buffaloe 1998) have not sampled rigorously when and where delta smelt were known to be abundant. Neither the recent studies, nor older evaluations (for example, Hallock and Van Woert 1959), sampled in a manner that allows elucidation of tidal or diel changes in delta smelt entrainment vulnerability. To address cumulative diversion effects, such as through use of coupled hydrodynamic-particle tracking models, it is necessary to understand when delta smelt are vulnerable to entrainment.

Examining how multiple species respond to similar situations often provides additional context and insight into the response of a target species (Swanson and others 2000; Bennett and others 2002). We compared and contrasted the entrainment dynamics and habitat use of delta smelt and two ecologically similar but non-native, small (typically <100 mm adult size), open-water fishes (Moyle 2002): threadfin shad, *Dorosoma petenense*, and inland silverside, *Menidia beryllina*, to address the following questions.

1. What is the relative effectiveness of the fish screens at Horseshoe Bend for excluding small open water fishes?

2. Is delta smelt, threadfin shad, and inland silverside entrainment through an unscreened diversion influenced by tidal and/or diel cycles, and if so, do entrainment dynamics differ among species?

3. Do delta smelt, threadfin shad, and inland silverside occur in different microhabitats, and if so, what

implications do these differences have for entrainment vulnerability and entrainment dynamics?

Hereafter, delta smelt, threadfin shad, and inland silverside are referred to as smelt, shad, and silverside, respectively.

Methods

We sampled simultaneously for fishes entrained through adjacent screened and unscreened agricultural diversions at Horseshoe Bend on the lower Sacramento River. The Horseshoe Bend diversions are siphon diversions. After priming, diversion flows are controlled by valves in the pipes and differences in water elevation on the river and island sides of its levee. Therefore, changes in tidal stage affect the volume of water flowing through the diversion. Samples were collected from 1207 h on July 12, 2000, to 0736 h on July 14, 2000, and from 1728 h on July 9, 2001, to 0750 h on July 11, 2001. These dates were chosen to (1) sample when delta smelt abundance was high in the lower Sacramento River, (2) sample at a time when irrigation water demand was sufficient to allow for extended continuous sampling, and (3) allow separation between tidal and diel influences on fish entrainment. During 2000, peak tidal stages occurred in the middle of the night and mid-morning. In 2001, peak tidal stages occurred around sunset and sunrise.

Fish were collected using two, 1.6-mm mesh, hooped plankton nets. The nets fit the diversion outfall pipes so that when fishing they sampled 100% of the diverted flow. (Please see Matica and Nobriga, p. 38, this issue, for additional details.) Net contents were collected at approximately hourly intervals. However, samples were not collected between 2148 h and 0022 h on July 12–13, 2000 because personnel were unavailable. At the end of each sampling interval, the nets were retrieved and the contents of the cod ends were placed into separate buckets. When possible, fish ≥25 mm total length (TL), or fork length (FL) if the caudal fin was forked, were measured and identified to species on site. All fish that could not be identified in the field were preserved in 10% formalin and identified in the laboratory. All Osmerid fishes (smelt), regardless of length, were preserved and identified in the laboratory. In 2000, only length ranges from each sample were recorded for common fishes other than smelt. In 2001, up to 50 randomly selected individuals of each species from each preserved sample

were measured for TL. Additional specimens were tallied, but not measured. The volume of water sampled during each interval was estimated using General Oceanics propeller flow meters. Water temperature (°C) in the irrigation canal also was measured with most net samples.

Catch was summarized as number collected and density (CPUE) as number of fish per 10,000 m^3 of water diverted. We explored potential tidal and diel influences on entrainment through the unscreened siphon using scatterplots and ANCOVA techniques based on categorical and continuous explanatory variables (Table 1). Explanatory variables were considered significant if the probability of their t-statistic was <0.05.

Table 1 Description of tidal and diel explanatory variables used in exploratory regression analyses of factors associated with delta smelt, threadfin shad, and inland silverside entrainment.

Predictor	Source	Definition	Interpretation
Tidal flow	DSM-2[a]	Estimated flow as m^3/s in Horseshoe Bend; converted from 15-minute intervals to average for each of our sampling intervals	+ coefficient = highest entrainment on ebb tides; – coefficient = highest entrainment on flood tides
Absolute value of tidal flow	DSM-2[a]	same as above	+ coefficient = highest entrainment at high tidal flow regardless of flow direction; – coefficient = highest entrainment at low tidal flow (slack tides)
Day-Night	Tides & Currents 2.2	day = 51%-100% of sample taken after sunrise and before sunset	+ coefficient = higher nighttime entrainment – coefficient = higher daytime entrainment
Crepuscular	Tides & Currents 2.2	crepuscular = 51%-100% of sample taken ± 2 hours of sunset or sunrise	+ coefficient = higher entrainment during crepuscular periods; – coefficient = higher entrainment during middle of day or night

[a]DWR Delta Simulation Model-2 (http://modeling.water.ca.gov/delta)

The ANCOVA results lead us to hypothesize that smelt entrainment may have been influenced by the amount of water diverted during each sample interval (or one of its correlates like water velocity at the siphon intake). To test this hypothesis, we divided each year's samples in half, based on the volume of water diverted during each sample interval. We used randomization tests (Haddon 2001) to compare the observed difference in mean number of smelt entrained in the lower 50% of volumes diverted to the mean number entrained in the higher 50% of volumes diverted. We used the number of smelt entrained per interval rather than smelt CPUE to remove the predictor

variable (volume sampled) from the response (smelt catch). The randomization technique compared the observed mean differences in smelt catch at low versus high volumes diverted to probability distributions of differences derived by iteratively randomly resampling the actual datasets 1,000 times. The reported P values represent the proportion of randomly derived mean differences that equalled or exceeded the observed mean differences. The significance level chosen for the randomization tests was $\alpha = 0.05$.

We also used randomization tests to test for day versus night differences in the sizes of smelt and shad entrained through the unscreened siphon. Samples were grouped into "day" or "night" as described in Table 1. Silverside were not included in this analysis because none were collected in 2000 and they were only collected at night in 2001. We tested day-night differences in size of shad entrained using only the 2001 data because shad length data were recorded as ranges in 2000. Over 1,000 shad were measured in 2001, but most were collected at night, so length differences were tested using a random subsample of 50 fish collected during daylight and 50 fish collected at night.

We compiled relative abundance data for smelt, shad, and silverside from Delta monitoring programs that had sampled in and near Horseshoe Bend near the time of our diversion sampling. To compare relative abundance in offshore habitats, we used mean CPUE of smelt, shad, and silverside from the four 20-mm Delta Smelt Survey stations nearest the diversion facility (see web site at http://delta.dfg.ca.gov/data/20mm). The four stations we considered are all within the tidal excursion range of the study site, so it was theoretically possible for fish at any of the stations to be transported past the diversion point with each tidal cycle.

We used beach seine (30 m x 1.5 m; 3.2 mm mesh) data to compare relative inshore abundance of smelt, shad, and silverside. The seine samples were taken in Horseshoe Bend along about 1 km of beach on the bank opposite the diversion facility. For each species, we estimated average CPUE and standard errors from five seine hauls taken from 1832 h on July 11, 2000, to 0432 h on July 12, 2000, and six hauls taken from 1620 to 2044 h on June 29, 2001. Note the mesh size of the seine was twice that of the diversion and 20-mm Survey nets. Thus, quantitative

comparisons of CPUE among gear types are not appropriate.

Results

We sampled over 115,000 m^3 of diverted water in over 2,000 minutes of sampling each year (Table 2). Although we intended to have flows evenly distributed through the screened and unscreened diversions, flow through the unscreened diversion actually comprised about two-thirds of the total volume diverted during both years. Mean water temperature was about 2 °C higher on average in 2001.

Table 2 Summary of sampling effort at the Horseshoe Bend diversion facility, and water temperature in the outflow pool, July 12-14, 2000, and July 9-11, 2001.

	Screened diversion		Unscreened diversion	
	2000	2001	2000	2001
Number of samples	36	34	36	34
Volume sampled (m^3)	41,242	40,651	78,420	92,419
Mean flow (m^3/s; ± standard deviation)	0.28 ± 0.15	0.31 ± 0.10	0.61 ± 0.06	0.75 ± 0.14
Minutes sampled	2,271	2,115	2,127	2,013
Mean sample duration (minutes ± standard deviation)	65 ± 13	61 ± 8	59 ± 6	58 ± 8
Mean time between samples (minutes ± standard deviation)	5 ± 3	6 ± 3	9 ± 3	8 ± 4
Mean water temperature (ºC ± standard deviation)	19.7 ± 0.7	21.8 ± 0.6		

The Horseshoe Bend fish screens were extremely effective at reducing the entrainment of smelt, shad, and silverside. In 2000 we collected 59 shad (13 to 59 mm) and 12 smelt (19 to 30 mm) from 36 unscreened diversion samples, but only one 19 mm shad from 36 screened diversion samples. No silverside were collected in 2000. In 2001, we collected 7,824 shad (9 to 42 mm), 31 smelt (16 to 45 mm), and 160 silverside (15 to 37 mm) from 34 samples of the unscreened diversion. Only 17 shad from 10 to 22 mm were collected from 34 screened diversion samples. Relative to the unscreened diversion, the screen excluded 99.8% of the shad and 100% of the smelt and silverside with both years combined. The high percentages of fish excluded by the screens indicated the screens perform better than designed. The Horseshoe Bend fish screens were designed to exclude smelt greater than about 25 mm long. As indicated by mean sizes below, many of the fish entrained through the unscreened diversion were <25 mm, and therefore could have

theoretically passed through the screen. However, the nearly 100% reduction of entrainment loss through the screened diversion relative to the unscreened diversion shows even larval fish were usually excluded. We do not know whether fish were impinged on the screens.

Smelt, shad, and silverside entrainment through the unscreened siphon was episodic or cyclic (Figure 1A, 1B). In other words, entrainment rates were not consistent among samples, suggesting environmental or behavioral influences on entrainment risk. In addition, peak entrainment rates of each species were staggered in time, which suggests different factors (or combinations of factors) influenced each species. Silverside were only entrained at night (Figure 1B). The day-night difference in silverside entrainment was statistically significant (Table 3). The significant negative crepuscular term (Table 3) resulted from maximum entrainment near the middle of the night (Figure 1B). Silverside entrainment was not statistically associated with either version of the tidal flow variable (Table 3).

Shad were entrained during both day and night (Figure 1A,1B), but shad entrainment was significantly higher at night in both 2000 and 2001 (Table 3). The diel differences in shad entrainment were due in part to an increase in the size of shad vulnerable to entrainment at night. During daylight, the mean TL of shad entrained through the unscreened siphon was 15.7 mm. At night, the mean TL of entrained shad increased to 21.8 mm. Based on a randomization test, the day-night length differences were statistically significant ($P < 0.001$). Shad entrainment was inversely correlated with tidal flow in both years (Table 3) because maximum shad entrainment occurred during nighttime flood tides (Figure 2A, 2B). During daylight, shad entrainment showed no relationship to tidal flow in 2000 (Figure 2A), but showed a nonlinear relationship to tidal flow in 2001 (Figure 2B). This daytime relationship is represented as a linear correlation with the absolute value of tidal flow in the 2001 ANCOVA model (Table 3).

Table 3 ANCOVA models for factors influencing entrainment of delta smelt, *Hypomesus transpacificus*, threadfin shad, *Dorosoma petenense*, and inland silverside, *Menidia beryllina*, collected from samples of an unscreened diversion in Horseshoe Bend, July 12-14, 2000 and July 9-11, 2001

Year	Species	Predictor	Coefficient	SE of Coefficient	$|T|$	P
2000	delta smelt	constant	0.454	0.576	0.79	0.44
		day-night	0.231	0.291	0.80	0.43
		crepuscular	−0.0766	0.286	0.27	0.79
		tidal flow	1.00E-03	4.47E-04	2.25	0.03
		absolute value of tidal flow	−9.07E-04	1.06E-03	0.85	0.40
		Adjusted R^2	0.05			
	threadfin shad	constant	−1.77	0.764	2.32	0.03
		day-night	1.54	0.386	3.98	<0.001
		crepuscular	0.593	0.379	1.56	0.13
		tidal flow	−1.96E-03	5.93E-04	3.31	0.002
		absolute value of tidal flow	2.51E-04	1.41E-03	0.18	0.86
		Adjusted R^2	0.43			
2001	delta smelt	constant	−0.364	0.81	0.45	0.66
		day-night	−0.227	0.319	0.71	0.48
		crepuscular	1.19	0.332	3.59	0.001
		tidal flow	1.83E-05	5.69E-04	0.03	0.98
		absolute value of tidal flow	−1.22E-03	1.33E-03	0.92	0.37
		Adjusted R2	0.28			
	threadfin shad	constant	1.49	0.962	1.55	0.13
		day-night	3.35	0.379	8.83	<0.001
		crepuscular	−0.0985	0.395	0.25	0.81
		tidal flow	−1.79E-03	6.76E-04	2.65	0.01
		absolute value of tidal flow	−3.64E-03	1.58E-03	2.31	0.03
		Adjusted R^2	0.73			
	inland silverside	constant	−0.882	0.876	1.01	0.32
		day-night	2.78	0.345	8.05	<0.001
		crepuscular	−1.06	0.359	2.96	0.006
		tidal flow	4.01E-04	6.15E-04	0.65	0.52
		absolute value of tidal flow	−1.56E-03	1.44E-03	1.09	0.29
		Adjusted R^2	0.68			
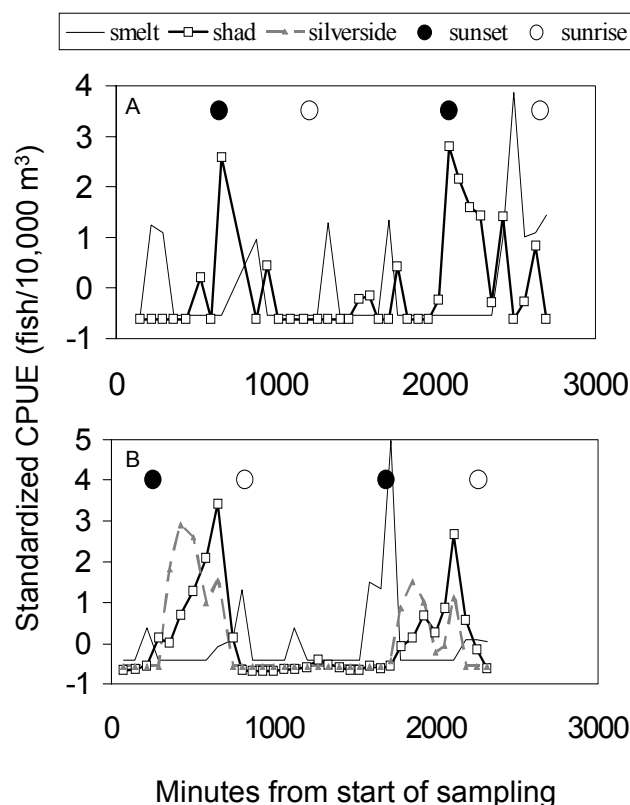
Figure 1 Time series of delta smelt, threadfin shad, and inland silverside collected per 10,000 m³ of water sampled (CPUE) from the unscreened irrigation diversion at Horseshoe Bend; A) July 12-14, 2000 and B) July 9-11, 2001. CPUE for each species was standardized to a mean of zero and standard deviation of one to facilitate interspecies comparisons.

Factors associated with smelt entrainment were not consistent. Smelt entrainment was weakly positively correlated with tidal flow in 2000, but not 2001 (Table 3; Figure 2C,2D). In 2001, smelt entrainment was significantly crepuscular, but not in 2000 (Figure 1A,1B). In both years, smelt entrainment had a single large peak (Figure 1A,1B), which likely had a large influence on statistical results (Figure 2C,2D). We hypothesized that tidally influenced changes in the volume of water diverted per sample interval (or a correlate like velocity at the diversion intake) might have been a factor influencing smelt entrainment. However, randomization tests indicated there were no significant differences in the numbers of smelt entrained at high versus low volumes of water diverted in either 2000 ($P = 0.06$) or 2001 ($P = 0.61$). In other words, smelt "catch" was not related to "effort."
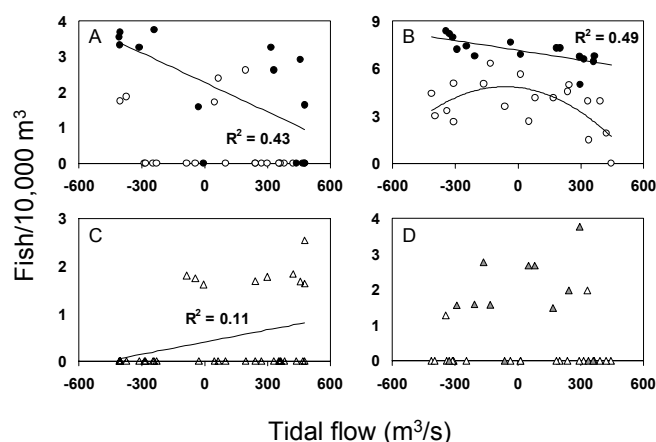


Figure 2 Relationships between tidal flow and fish catch per unit effort from the unscreened diversion at Horseshoe Bend for (A) threadfin shad in 2000, (B) threadfin shad in 2001, (C) delta smelt in 2000, and (D) delta smelt in 2001. Significant diel differences in entrainment are represented by different symbols. Open circles represent daytime samples (panels A and B) and open triangles represent no diel difference (panel C). Filled circles represent nighttime samples (panels A and B) and filled triangles represent crepuscular samples (panel D). Regression lines are included where tidal flow relationships are statistically significant at $\alpha = 0.05$.

The mean lengths of delta smelt did not differ significantly between day and night in either year (2000: daytime mean = 22.8, nighttime mean = 27.7; $P = 0.06$; 2001: daytime mean = 27.6, nighttime mean = 29.3; $P = 0.51$). Overall, our results suggest smelt entrainment was random with regard to tidal or diel cycles.

In both 2000 and 2001, smelt were more abundant than shad and silverside in mid-channel trawl surveys in and near Horseshoe Bend (Figure 3A). In both years, silverside was the most abundant fish in nearshore seine surveys of Horseshoe Bend (Figure 3B) and was completely absent from trawl surveys (Figure 3A). Shad were collected in the trawl surveys at low CPUE (Figure 3A). Shad were not collected during the 2000 seine survey, but were nearly as abundant as silverside during the 2001 seine survey (Figure 3B). These data suggest smelt tend to remain offshore, whereas shad and silverside are relatively abundant inshore. We suggest inconsistent smelt entrainment dynamics reflected a tendency for smelt to largely remain in offshore habitats, coming into contact with the diversion inconsistently. In contrast, we hypothesize that shad and silverside entrainment

dynamics were consistent because they extensively occur in nearshore habitats, potentially becoming susceptible to the diversion whenever they are active or lose visual cues (at night). Assuming each gear estimates fish relative abundance between years, these hypotheses are further supported by the observation that lower shad and silverside entrainment in 2000 is consistent with lower relative abundance based on the seine and trawl data. In contrast, the lower entrainment of smelt in 2000 is not consistent with its apparent relative abundance in trawl data from 2000 and 2001 (Figure 3A).
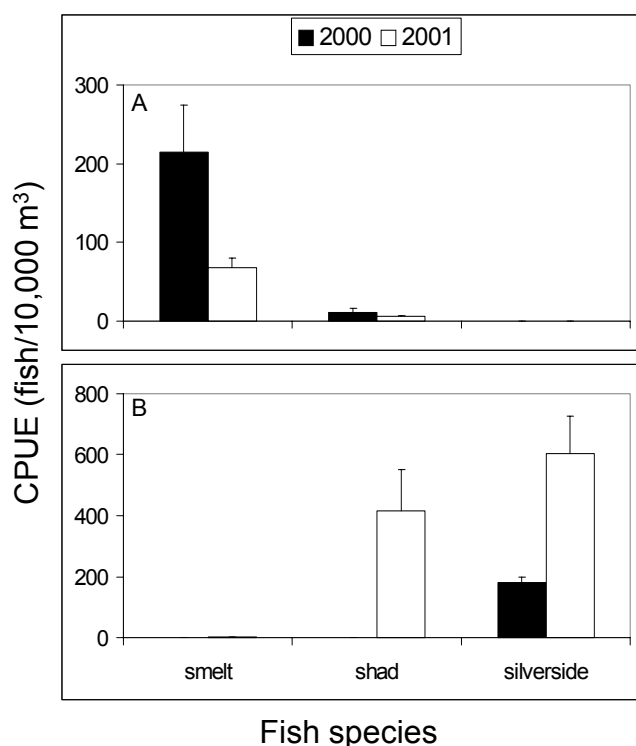
Figure 3 Average catch per unit effort (with standard error bars) of delta smelt, threadfin shad, and inland silverside from IEP monitoring surveys. (A) stations 704–707 of 20 mm Delta smelt Survey 9 in 2000 and stations 704–707 of 20-mm Delta Smelt Survey 8 in 2001 (http://www.delta.dfg.ca.gov/data/20mm); (B) Shallow Water Monitoring Methodology Seine Surveys in Horseshoe Bend, July 11–12, 2000 and June 29, 2001.

Discussion

This study provided the longest continuous monitoring of fish entrainment at a Delta agricultural diversion facility to date. Generally, our results suggest entrainment risk is strongly influenced by the presence or absence of a fish screen and by diel cycles. Tidal cycles and a tidally influenced variable (magnitude of diversion flows) appeared to have comparatively minor to no influence on fish entrainment dynamics. We acknowledge our results may not be representative of entrainment dynamics at other Delta diversions.

Relative to the unscreened diversion, the screen excluded 99.8% of shad and 100% of smelt and silversides (both years combined). The 2.4 mm screen mesh was designed to exclude smelt > 25 mm long. We do not know whether debris accumulation or biofouling reduced the nominal screen mesh size. However, as indicated by mean lengths, many fish (mostly shad) entrained through the unscreened diversion were < 25 mm, and therefore could have theoretically passed through the screened diversion. Postlarval shad and smelt are morphologically similar (Wang 1986), so we suspect virtually all smelt over about 15-20 mm TL are excluded from diverted water at Horseshoe Bend during normal irrigation operations. We do not know whether fish impinged on the screen. However, we think it is unlikely large numbers of fish < 25 mm could impinge without eventually passing through because fish would most likely contact unimpeded high velocity sections of screen if fouling significantly reduced mesh size. The DWR has installed identical screens on four other lower Sacramento River diversions. Therefore, smelt < 25 mm may have more protection than anticipated from irrigation diversions in the lower Sacramento River.

Tidal-diel influences on entrainment are consistent with other studies. Tidal influences on fish behavior and distribution are common in estuarine environments (Dodson and others 1989; Schultz and others 2000). Diel changes in distribution (Wurtzbaugh and Li 1985; Bennett and others 2002), drift (Johnston and others 1995; Gadomski and Barfoot 1998) and entrainment vulnerability (Rulifson and Copeland 1982; Carter and Reader 2000) also are widely reported for young fishes. For the San Francisco Estuary, tidal and diel influences on delta smelt distribution have been reported (Aasen 1999; Bennett and others 2002). The diel influence on shad and silverside entrainment was substantial; daytime-only diverting at unscreened diversions might reduce entrainment of these fishes nearly as much as a fish screen (Figure 2). However, we found no evidence unscreened irrigation diversions could be operated to provide a similar level of protection (that is, > 90% reduction in entrainment) for smelt.

Flow variation through the unscreened diversion did not affect numbers of fish entrained, even the nearshore-oriented shad and silversides. This was surprising because all three species comprised young individuals, which would not be expected to have strong swimming abilities (all but one individual were < 50 mm long). Fish facilities design theory considers swimming ability of the target species when estimating appropriate approach velocities for diversions (Clay 1995). Approach velocity (m/s) at a diversion intake is an algebraic variant of flow through the diversion (m3/s). The lack of a diversion flow influence on and periodicity of fish entrainment at Horseshoe Bend provide evidence that fish loss was related more to distribution and/or behavior than to the hydrodynamic influence of the diversion. This hypothesis is supported by consideration of diversion influence relative to tidal influence in Horseshoe Bend. The maximum volume of water we estimated was diverted during one of our approximately hourly samples was 3,870 m3. During our sampling, peak flood and ebb flows through Horseshoe Bend removed 3,870 m3 of water in an estimated 8-9 seconds (DWR unpublished data). Further, at mean low water when there was no tidal exchange, Horseshoe Bend retained an estimated 5.4 million m3 of water. Clearly, the diversion had a very small influence on Horseshoe Bend hydrodynamics and therefore the movement of fish.

Combining the 2000-2001 study periods, we collected only 43 smelt during 69 hours of sampling 170,839 m3 of unscreened water, but low catch was not due to low abundance in the vicinity of the diversion. In each trawl survey summarized in this paper, 73% of the total smelt CPUE from all 41 stations was collected from the four stations nearest the diversion, suggesting the majority of the smelt standing stock was within the tidal excursion range of the diversion. We think the low numbers entrained reflect the small hydrodynamic influence of the Horseshoe Bend diversion and the offshore distribution of smelt. This may have implications for prioritizing fish screen locations to protect smelt.

Large-scale screening of small diversions is an attractive restoration concept because it may have multiple species benefits and because even low loss rates to unscreened diversions may represent an unacceptably large source of mortality for a threatened species like delta smelt. However, large-scale screening has been criticized because it would be very costly and the ecological benefits are uncertain. Fish screens also require

considerable maintenance to keep them operating at = 6 cm/s recommended for delta smelt protection (http://iep.water.ca.gov/cvffrt). This has been a problem at Horseshoe Bend. Fouling and corrosion coupled with inadequate maintenance have resulted in screen malfunctions in four of their five years of operation.

Results from the present study suggest entrainment losses are strongly affected by fish habitat use and diel behavior. A detailed understanding of these factors could help fisheries managers (1) prioritize locations for fish screens, (2) recommend strategies that reduce entrainment losses at unscreened diversions, and (3) improve the performance of coupled hydrodynamic-particle tracking models. However, additional research is needed to better understand the effect of hydrodynamics. Although our results suggested a relatively small role of tidal dynamics, additional sampling is needed in channels with different volumes and tidal regimes. For example, we expect the hydrodynamic influence of small irrigation diversions must be lower in large Delta channels (mainstem Sacramento and San-Joaquin rivers) and flooded agricultural islands than in Horseshoe Bend, which has considerably less volume (DWR unpublished data). Irrigation diversions also must have larger hydrodynamic influences in Delta channels that are smaller than Horseshoe Bend. Spatio-temporally expanded studies also are needed for the horizontal and vertical distribution of young smelt over tidal-diel cycles. Smelt move into shallow water to facilitate retention in low salinity zone embayments of the western Delta and areas downstream (Aasen 1999; Bennett and others 2002), but tidally-oriented inshore movement was not observed in a Delta channel (Aasen 1999). To resolve this apparent disparity, we recommend coupling behavioral studies with simultaneous monitoring studies of channel and diversion hydrodynamics. Ultimately, a modeling approach will probably be needed to confirm a large-scale screening program for Delta irrigation diversions is an effective component of a comprehensive restoration strategy for delta smelt and other species.

Acknowledgments

References

Aasen GA. 1999. Juvenile delta smelt use of shallow-water and channel habitats in California's Sacramento-San Joaquin Estuary. California Fish and Game 85:161–9.

Arthur JF, Ball MD, Baughman MY. 1996. Summary of federal and state water project environmental impacts in the San Francisco Bay-Delta Estuary, California. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): Pacific Div AAAS. p 445–95.

Bennett, WA, Moyle, PB. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. In: Hollibaugh JT, editor. San Francisco Bay: the ecosystem. San Francisco (CA): Pacific Div AAAS. p 519–42.

Bennett, WA, Kimmerer, WJ, Burau, JR. 2002. Plasticity in vertical migration by native and exotic estuarine fishes in a dynamic low salinity zone. Limnology and Oceanography. Forthcoming.

[CALFED] CALFED Bay-Delta Program. 2000. Programmatic Record of Decision. Available via the Internet at: http://calfed.ca.gov/current/ROD.html Accessed July 2002.

Carter KL, Reader JP. 2000. Patterns of drift and power station entrainment of 0+ fish in the River Trent, England. Fish Manag Ecol 7:447–64.

Clay CH. 1995. Design of fishways and other fish facilities, 2nd edition. Boca Raton (FL): Lewis Publishers.

Cook L, Buffaloe L. 1998. Delta agricultural diversion evaluation summary report, 1993–1995. Interagency Ecological Program for the San Francisco Bay/Delta Estuary Technical Report 61. Sacramento (CA): California Department of Water Resources. 80 p.

Dadswell MJ, Rulifson RA. 1994. Macrotidal estuaries: a region of collision between migratory marine animals and tidal power development. Biol J Linnaean Soc 51:93–113.

Dodson JJ, Dauvin J-C, Ingram RG, D'Anglejan B. 1989. Abundance of larval rainbow smelt (*Osmerus mordax*) in relation to the maximum turbidity zone and associated macroplanktonic fauna of the middle St. Lawrence Estuary. Estuaries 12:66–81.

Gadomski DM, Barfoot CA. 1998. Diel and distributional abundance patterns of fish embryos and larvae in the lower Columbia and Deschutes rivers. Env Biol Fishes 51:353–68.

Gehrke PC. 1992. Diel abundance, migration and feeding of fish larvae (Eleotridae) in a floodplain billabong. J Fish Biol 40:695–707.

Haddon M. 2001. Modeling and quantitative methods in fisheries. Boca Raton (FL): Chapman & Hall/CRC. 406 p.

Hallock RJ, van Woert WF. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. California Fish and Game 45:227–96.

Herren JR, Kawasaki SS. 2001. Inventory of water diversions in four geographic areas in California's Central Valley. In: Brown RL, editor. Fish Bulletin 179. Contributions to the biology of Central Valley salmonids, volume 2. Sacramento (CA): California Department of Fish and Game. p 343–55.

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vedlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol App 5:272–89.

Kingsford RT. 2000. Ecological impacts of dams, water diversions, and river management on floodplain wetlands in Australia. Austral Ecol 25:109–27.

Moyle PB. 2002. Inland fishes of California, revised and expanded. Berkeley (CA): Univ Calif Pr. 502 p.

Pickard A, Baracco A, Kano R. 1982. Occurrence, abundance, and size of fish at the Roaring River Slough intake, Suisun Marsh, California during the 1980–81 and the 1981–82 diversion seasons. Interagency Ecological Program for the Sacramento-San Joaquin Estuary Technical Report 3. Sacramento (CA): California Dept. of Water Resources. 14 p.

Rulifson RA, Copeland BJ. 1982. Traveling screens as sampling gear for vertical distribution studies. Estuaries 5:82–94.

Spaar S. 1994. Delta agricultural diversion evaluation 1992 pilot study. Technical Report 37. Interagency Ecological Program for the San Francisco Bay/Delta Estuary. Sacramento (CA): California Dept. of Water Resources. 37 p + appendices.

Swanson C, Young PS, Cech JJ, Jr. 1998. Swimming performance of delta smelt: maximum performance, and behavioral and kinematic limitations on swimming at submaximal velocities. J Exp Biol 201:333–45.

Swanson C, Reid T, Young PS, Cech JJ, Jr. 2000. Comparative environmental tolerances of threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an altered California estuary. Oecologia 123:384–90.

Swanson C, Young PS, Cech JJ, Jr. 2002. Draft research findings: interpretations and potential applications for fish screen flow and operational criteria from the fish treadmill project. Anadromous Fish Screen Program, Cooperative Agreement No. 114201J075.

Sweetnam DA. 1999. Status of delta smelt in the Sacramento-San Joaquin Estuary. California Fish and Game 85:22–7.

Wang JCS. 1986. Fishes of the Sacramento-San Joaquin Estuary and adjacent waters, California: a guide to the early life histories. Interagency Ecological Program Technical Report 9. Sacramento (CA): California Department of Water Resources.

Wurtsbaugh W, Li H. 1985. Diel migrations of a zooplanktivorous fish (*Menidia beryllina*) in relation to the distribution of its prey in a large eutrophic lake. Limnol Oceanog 30:565–76.

Revision of California Department of Fish and Game's Spring Midwater Trawl and Results of the 2002 Spring Kodiak Trawl

Kelly Souza (DFG), ksouza@delta.dfg.ca.gov

The Department of Fish and Game (DFG) has conducted the Spring Midwater Trawl Survey (SMWT) annually since 1991, as an extension of the Fall Midwater Trawl Survey (FMWT), to monitor the winter and spring distribution and abundance of delta smelt (*Hypomesus transpacificus*). The information collected was intended to provide an indication of adult spawning distribution favoring the eastern or southern Delta, which could lead to increased adult salvage at the south Delta water export facilities and potentially result in high juvenile salvage later in the year. The SMWT employed the same protocols and gear as the FMWT survey (Souza 2002), but did not sample all of the San Pablo Bay stations.

In September 1994, a special survey designed to investigate the efficiency of various nets at capturing delta smelt, developed evidence strongly suggesting the current midwater trawl gear and protocol was not as effective as the U.S. Fish and Wildlife (USFWS) Chipps Island trawl or a Kodiak trawl. Replicate side-by-side surface tows were conducted with all three trawls and the density of delta smelt from each trawl was compared. Density data from these comparisons strongly suggested the Kodiak trawl was much more efficient at capturing delta smelt than either the Chipps Island trawl or the conventional midwater trawl. Therefore, beginning with the 2002 sampling season, the midwater trawl gear was replaced with a Kodiak trawl to take advantage of its greater catch efficiency and improve the detection rate of pre-spawning delta smelt. Potentially, this will enable us to better inform water export facility operators of the potential to entrain adult delta smelt and their offspring.

The 2002 SKT sampled four days during the first week of each month from January through March. To offset the additional costs of an added boat operator, and an additional boat, the number of stations were reduced, to

decrease the duration of the survey. This also addressed another concern, which was exceeding allotted take limits of delta smelt. The 100 SMWT stations were reduced to 41 stations extending from Napa River east, to Walnut Grove on the Sacramento River, and Stockton on the San Joaquin River (Figure 1). The majority of the stations were existing sample sites from DFG's Townet Survey. They were chosen because the stations are evenly distributed throughout the Sacramento-San Joaquin Delta and already known to our boat operators. Additionally, eight FWMT stations located in the North and South Mokelumne rivers and Cache Slough were added to increase the spatial distribution into areas of potential spawning.

A standard Kodiak trawl (mouth opening of 7.1-m by 1.7-m and 64-mm cod-end mesh) was surface-towed for 10 minutes. All fish, except delta smelt, were measured to the nearest millimeter and released. All delta smelt were preserved in formalin and brought back to DFG Stockton, to obtain sex and maturity status (stage of gonadal development).

To examine the maturity stage of delta smelt specimens, three incisions were made to the left side of the body. The first incision was vertically from the vent to the lateral line. The second incision was horizontally across the

lateral line to the pectoral fin. A vertical incision from the pectoral fin to the ventral-most part of the abdomen completed the opening. The "flap" created by these incisions was then pulled away from the body, and "macro-characteristics" were observed and recorded (Table 1).
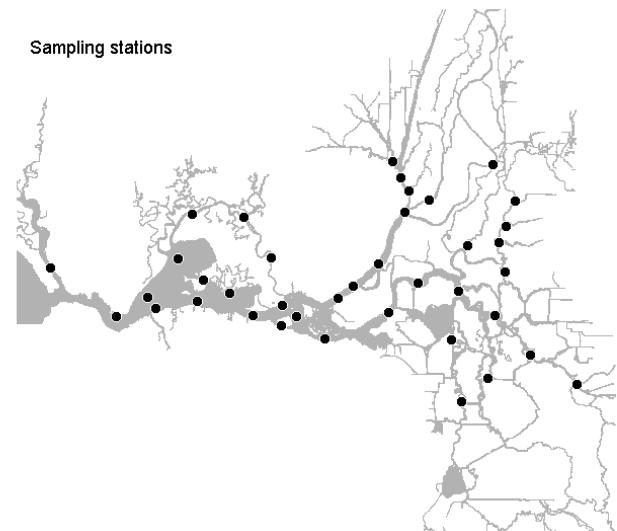
Figure 1 Locations of sampling stations for California Department of Fish and Game's Spring Kodiak Trawl Survey, Sacramento-San Joaquin Delta

Table 1 Macro-characteristics of male and female delta smelt (*Hypomesus transpacificus*) gonads used for obtaining maturity status of preserved specimens (Source: adapted from R. Mager, personal communication, see "Notes").

| Stage	Male	Female
I	Left testis is barely visible and the right testis is impossible to find. Gonads < 0.1% of body weight.	Left ovary translucent and grainy in texture. Right ovary difficult to impossible to find.
II	Testis visible as thin strands ventrolateral to the swim bladder. Gonads are less than 0.5% of body weight.	Not differentiated from stage 1 for this study.
III	Right testis is visible as a small pale white or grey cord. Left testis has developed in the central portion of the gonadal cord.	Individual oocytes slightly orange, 0.25 to 0.50 mm in diameter, and visible to the naked eye.
IV	Both testes are clearly visible, smooth, and pale white.	Abdomen is enlarged with egg mass and observable without dissection. Oocytes are bright orange and about 1 mm in diameter. Eggs can be stripped with gentle pressure.
V	Testes are bright white and very smooth. Testes account for 2% to 4% of body weight. Milt can be released by gentle pressure.	Oocytes are lager than 1 mm in diameter, and hydrated. Clear fluid surrounds the orange oocytes that become increasingly cloudy and degenerate.
VI	Testes and milt not as bright white as during stage V. During summer months, indicated by a decrease in size of testes.	Gonad is translucent and textured with a few leftover oocytes embedded in tissue. Loose abdomen easily detected.

Results

Distribution

The 2002 SKT caught 15,094 fish representing 17 species and 10 families. The most common fishes encountered were threadfin shad (*Dorosoma petenense*) (91%), followed by delta smelt (*Hypomesus transpacificus*) (7%). Other families collected (listed from most common to least common) were atherinidae, cyprinidae, salmonidae, gasterosteidae, percichthyidae, ictaluridae, petromyzontidae, and centrarchidae.

Distribution of delta smelt constricted as the survey progressed, with the largest concentration always occurring in Montezuma Slough. Densities at stations inside Montezuma Slough were very high and ranged from 8 to 32 smelt per 1000 m^3 and averaged 13.5 smelt per 1000 m^3. In January, distribution spanned from Carquinez Straits, through the confluence area, into the South Delta, and as far north as Cache Slough (Figure 2). The February distribution was more confined, with fewer delta smelt collected in the South Delta and Cache Slough. Distribution was centered in the Suisun Bay to lower Sacramento area (Figure 3). In March, a larger proportion of the catch (27%) came from the Sacramento River than in any other month however, the majority of delta smelt were still located in Montezuma Slough (Figure 4).
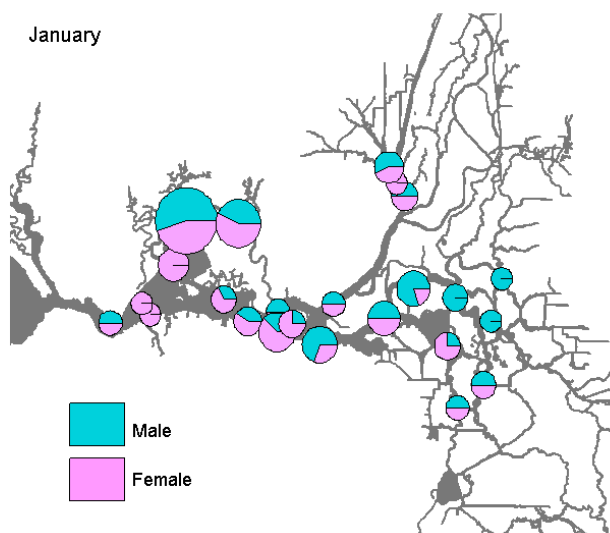
Figure 2 Distribution of male and female delta smelt (*Hypomesus transpacificus*) collected during January of the 2002 Spring Kodiak Trawl, Sacramento-San Joaquin Delta
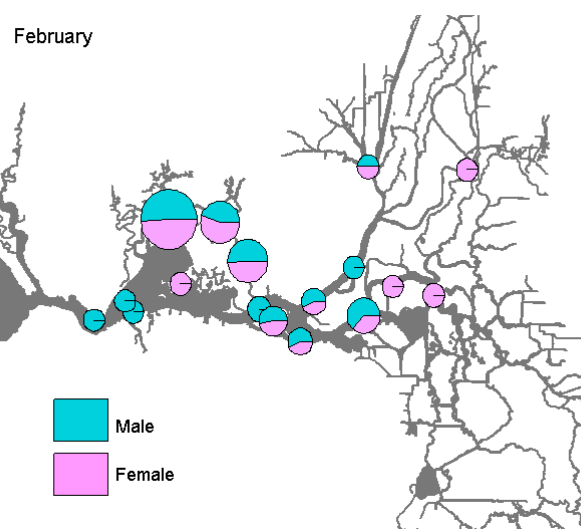
Figure 3 Distribution of male and female delta smelt (*Hypomesus transpacificus*) collected during February of the 2002 Spring Kodiak Trawl, Sacramento-San Joaquin Delta
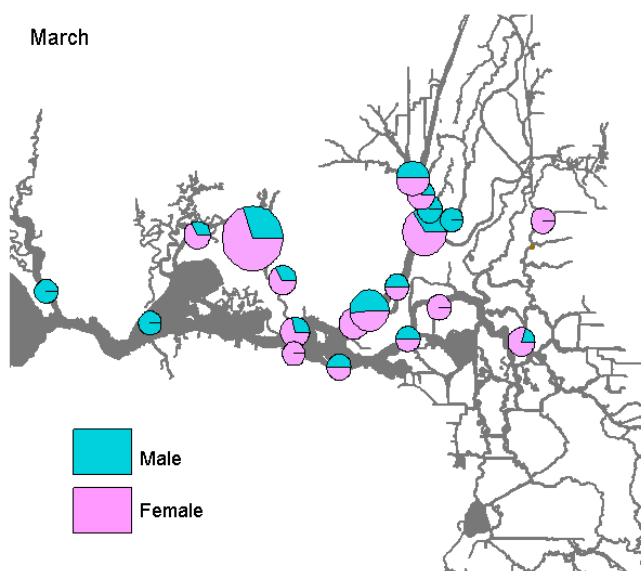
Figure 4 Distribution of male and female delta smelt (*Hypomesus transpacificus*) collected during March of the 2002 Spring Kodiak Trawl, Sacramento-San Joaquin Delta

Gonadal Staging

Examination of the gonadal stages of delta smelt revealed that sex ratios of delta smelt captured changed as the spawning season progressed. In January and February, the ratio of females to males was 1:1. This ratio increased to 2:1 in March. Possible explanations are (1) females persist

longer into the spawning season; (2) females become more vulnerable to the gear; or (3) males arrived sooner and left sooner. Gonadal staging results also indicate that males and females appear to be functionally mature at the same time and place. This was especially evident in March, when a large proportion of mature male and female delta smelt were collected in the Sacramento River. Previous to March, only 10 delta smelt were collected in the lower Sacramento, and none of them were functionally mature.

Females collected in January and February were predominately found to be Stage III (see Table 1), a long-lasting stage in which the oocytes are developing and enlarging with yolk (R. Mager, personal communication, see "Notes"). Males collected in January and February were found to be in middle and late recrudescence, the two stages prior to functional maturity (see Table 1). It was not until March that functionally mature males and females, and successfully spawned females were collected in the Sacramento River. Temperatures at which spent females were collected ranged from 12.2 °C to 12.8 °C. At this same time, no spent males were collected in the Sacramento River, but a large proportion of the males present were mature (Stage V), potentially ready to spawn at any time. The March survey also collected more delta smelt in Montezuma Slough than in the Sacramento River, however there was no evidence of spent individuals of either sex from Montezuma Slough. In March, 89% of the individuals caught were still unspawned, including Stage III females (oocytes still developing) and Stage IV males (late recrudescence). This indicates that the majority of spawning had not taken place by the end of the SKT survey.

The SKT was more successful than the SMWT for describing the distribution of delta smelt. A total of 895 delta smelt was collected, five times more than the average number of delta smelt collected during previous SMWT surveys (1991 to 2001). Sampling will continue next year, with a few modifications. To improve our temporal coverage of delta smelt, the duration of the survey will commence in the later half of February and extend into April (and possibly May). Sampling effort may also double to twice per month. To increase our spatial coverage of delta smelt, we are considering adding stations within Lindsay, Prospect, and Cache sloughs. (Detailed graphs and descriptions of gonadal maturity stages of delta smelt collected during all months of the SKT can be found at www.delta.dfg.ca.gov).

References

Souza K. 2002. Townet Survey and Fall Midwater Trawl Survey. IEP Newsletter (15)2:21–4

Notes

Mager RC. Department of Water Resources, Division of Environmental Services, Sacramento, California. June 14, 2002. E-mail communication.

Ocean Influences on Central Valley Salmon: The Rest of the Story

Louis W. Botsford, Department of Wildlife, Fish and Conservation Biology University of California, Davis

Abstract

There is increasing awareness of the strong influence of changing ocean conditions on variability in abundance of Pacific salmon throughout the northeast Pacific. Improved understanding of ocean variability can reduce the uncertainty in management of the associated freshwater resources by reducing the unexplained variance in observations. Ocean effects on Pacific salmon have been dominated by a regime shift in ocean conditions in the mid-1970s, leading to an increase in abundance of Alaska salmon and a decline in coho salmon in the California Current. On interannual time scales, ocean conditions related to El Niños appear to drive variability in coho and chinook salmon in the California Current. However, knowledge of these general regional effects is not sufficient to determine specific ocean effects on local, Central Valley populations. Sampling programs in the local coastal ocean will be necessary. Monitoring of local biological productivity and physical oceanographic conditions associated with variable upwelling winds, along with sampling of local juvenile salmon can be used to reduce the unexplained variability that hinders management of Central Valley salmon populations.

Introduction

The variable ocean phase has always been the more mysterious part of the salmon life history. Variability in salmon returns has been a strong force shaping human culture since before European arrival on the West Coast. Native populations too far upstream for reliable spawning runs (high variability) did not depend heavily on salmon as a staple, while for populations that did depend on salmon, the potential for occasional years of low abundance surely drove the formation of cultural rules to assure good runs (Taylor 1999). The annual celebration of the arrival of the first salmon was probably in part a celebration of good fortune brought about by the annual variability in runs.

This view of ocean variability as a strong, unknowable force continues into modern times. Rather than describing ocean variability explicitly, managers often find it more convenient to treat it simply as a focus of blame when abundance is low, while high abundance in periods of good ocean conditions is credited to good management. For example, the dramatic increase in salmon abundance in Alaska in the mid-1970s is often attributed to the Alaska Department of Fish and Game taking over salmon management from the federal government. As another example, a recent description in the *Sacramento Bee* of the dramatic recent increase in spawning returns of the endangered Sacramento River winter-run chinook salmon and the laudable steps that have been taken to bring that about, failed to mention the ocean or the telling fact that spawning abundance in many stocks along the coast of Washington, Oregon, and California have also increased in the last few years.

Research programs aimed at improving freshwater salmon production often ignore the ocean phase because nothing can be done to change ocean conditions, however, that rationale ignores the value of reducing uncertainty in decision making. An essential element of adaptive management is monitoring of the results of management for the purpose of learning more about the system so that management can be improved. Observations made in monitoring contain a certain degree of unexplained variability, which slows learning and the consequent response. If we can explain or reduce that unexplained variability we can understand the consequences of management better, respond more rapidly and attain management goals sooner. Ocean variability is typically the dominant source of unexplained variability in freshwater salmon research. Increased general understanding of the factors driving ocean salmon survival in the northeast Pacific and local monitoring of the conditions determining survival of our local populations could greatly improve ongoing research in the Sacramento-San Joaquin Bay-Delta system. Here I present a brief introduction to these.

Ocean Impacts on the Semi-Basin to Local Scale

Recent ocean variability in Pacific salmon has been dominated by the dramatic increase in abundance and catch of most Alaska species in the mid-1970s (Figure 1). There are well documented physical changes (a "regime shift") in the Gulf of Alaska in the mid-1970s that would be expected to change biological productivity (for example, mixed layer depth, Polovina and others 1994, 1995), as well as observed changes in chlorophyll levels (Venrick and others 1987) and zooplankton (Brodeur and others 1996). A concurrent inverse shift in ocean conditions in the California Current has been proposed on the basis of a change in the relative fractions of the West Wind Drift that provide nutrient rich water to the Alaska Gyre and the California Current System (CCS) (Chelton and 1982; Pearcy 1992; Francis and others 1998). While there is evidence for decadal scale changes in the California Current over this time period, it is not clear that the proposed transport mechanism is responsible, and we do not see a dramatic uniform change in the CCS in the mid-1970s. However, there is a continuing decline in zooplankton productivity off southern California (Roemmich and McGowan 1995), and observations of temperature and salinity before and after the mid-1970s indicate warmer fresher water in the later period, consistent with the inverse regime shift (Pennington and Chavez 2000).

The consequences of this regime shift for salmon populations in the California Current are species specific (Figure 1). Catch records indicate coho salmon declined throughout the CCS in the mid-1970s, while chinook salmon did not. In fact, a closer look at total salmon catches in Alaska, by individual species, indicates that even there, total chinook salmon catch did not increase dramatically in the regime shift of the mid-1970s.

Alaska Salmon Catch
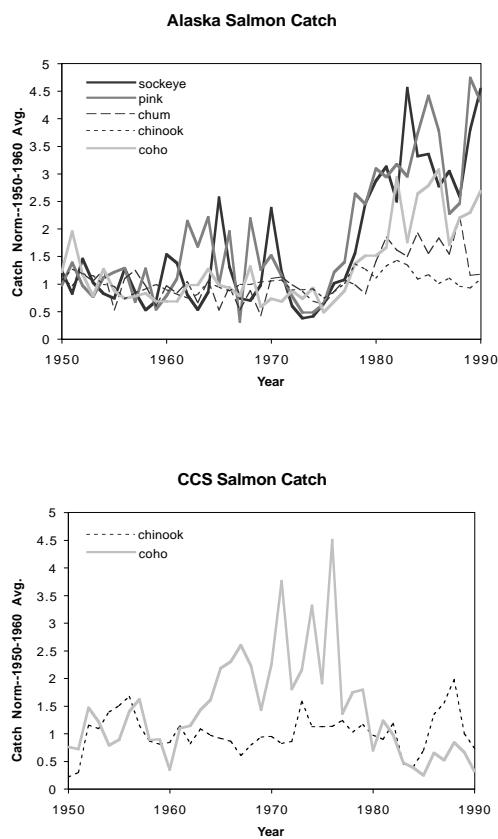
CCS Salmon Catch

Figure 1 Salmon catches in Alaska and the California Current System (CCS) (both normalized to average catch between 1950 and 1960 to show the relative increase in each species) indicate upper trophic level effects of a regime shift in physical conditions in the mid-1970s in the northeast Pacific. Catch of some, but not all, salmon species increased in Alaska in the mid-1970s, while catch of one species in the CCS declined uniformly.

Closer examination of the spatial distribution of salmon catch in the CCS over the period from the 1950s through the 1980s (when effort limitations began to affect catch) reveals differences in the time and space scales of variability catch (Botsford and Lawrence 2002). Coho salmon vary coherently along the coast, and seem to respond to annual variability, while chinook salmon have a patchy spatial distribution of variability and vary temporally on two- to five-year time scales (Figure 2). A spatial principle components analysis indicated that central California catches covary with catches from central Oregon, while catches elsewhere had the opposite phase. Analysis of the available indicators of ocean state over the same period revealed a strong covariabiltiy between ocean temperature, sea level, and the Bakun upwelling index (Botsford and Lawrence 2002). The first

principle component of these explains a majority of the variance, and the loadings (positive temperature, positive sea level and negative upwelling index, all approximately equal) reflect well-known conditions associated with El Niño off the California coast. This principle component, termed the California Current Index, is significantly correlated with coho salmon catch at lags indicating an effect on the age of ocean entry and the age of return to freshwater to spawn. For chinook salmon it is correlated only at a lag indicating an effect on the age of return, but the lack of correlation associated with the age of entry may be due to the variability in spawning age distributions among chinook populations. The California Current index is closely related to indicators of ocean conditions in the north Pacific, such as the Pacific Decadal Oscillation (Mantua and others 1997).

Figure 2 The spatial distribution of catch for coho salmon and chinook salmon in the California Current System (data from PMSFC). To emphasize spatial covariability, the catch series at each location was divided by its mean. Note that coho salmon collapsed coast-wide in the mid-1970s, while chinook salmon did not.

Earlier studies of Central Valley chinook salmon local populations are consistent with these findings. Correlations between abundance of Sacramento River fall-run chinook and an index of ocean conditions similar to the CCI, for the years 1962–1983 indicated a negative effect of El Niño conditions during the year of return (age 3) (Kope and Botsford 1990). In addition, analysis of coded wire tag returns for the same run for brood years 1977–1984 indicated that survival was positively

correlated with Bakun's upwelling index in the year of ocean entry for hatchery fish released in the bay or estuary, but survival of fish released in the Sacrament River was not (Cramer 1992). Visual inspection of escapements from the dominant fall run indicates they seem to follow ocean conditions, increasing to high levels in the mid to late 1980s following the strong El Niño in 1982–83, then remaining at low levels during the protracted weak El Niño during the early 1990s, increasing then decreasing during the 1997–1998 El Niño and increasing in response to better ocean conditions in 1999–2000 (Figure 3).
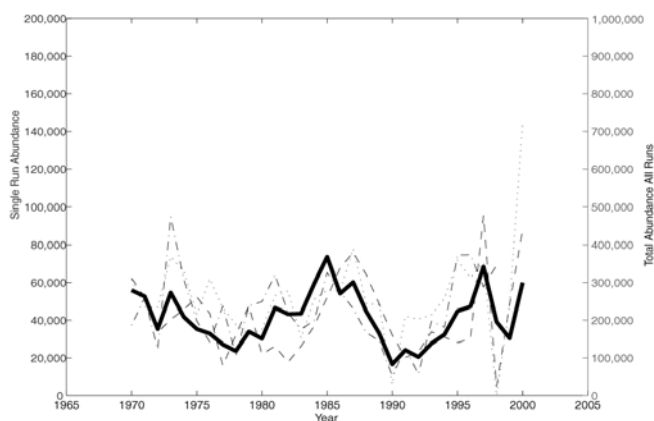
Figure 3 Catch of the three largest components of the fall run chinook salmon in the Sacramento River system, the main stem Sacramento River (dashed line), the Feather River (dotted line) and the American River (dots and dashes). Also shown is the total catch from all runs that are counted (bold line).

There are indications that the ocean conditions reached by the regime shift of the mid-1970s may be reversing themselves. Zooplankton composition at three locations—southern California, central Oregon, and British Columbia—all indicate greater abundance of more northern species, and lower abundance of southern species since 1999 (Batchelder and others 2002). In addition, salmon survivals, such as the Oregon Production Index, have increased and salmon spawning returns in many streams along the coast have increased in 2000 and 2001.

Studies of Local Oceanographic Mechanisms

While the changes in ocean conditions and salmon over the past 50 years provide evidence for dramatic ocean influences, and a context for possible variability in local populations, differences among species and locations also indicate that conditions at even the regional scale cannot be relied upon to indicate year-to-year effects of the ocean on local populations. Monitoring of local ocean conditions, and knowledge of their effects on salmon survival are necessary. Fortunately, studies of local conditions indicate how varying winds affect local ocean circulation and biological productivity in the primary local nursery area (the Gulf of the Farallones), and the technology is available for continued monitoring and research.

For the past decade, researchers at the University of California at Davis have been studying the effects of local circulation on productivity and settlement of meroplanktonic larvae of local invertebrates. While the primary focus of that study is on how circulation near Pt. Reyes leads to settlement of sea urchins and crabs along the coast north of Pt. Reyes, settlement of one taxonomic group, non-cancrid crabs (porcellanids, grapsids, pagurids, and majids), appears to reflect biological conditions in the California Current in general (El Niño vs. non-El Niño conditions) (Lundquist and others 2000). There is greater settlement of this group in non-El-Niño years, as indicated by the decline in settlement with temperature over most of the years in Figure 4. The single exception is 1999, one of the strongest upwelling years on record, when though productivity may have been good, it may have been lost by being entrained in the strong offshore transport.
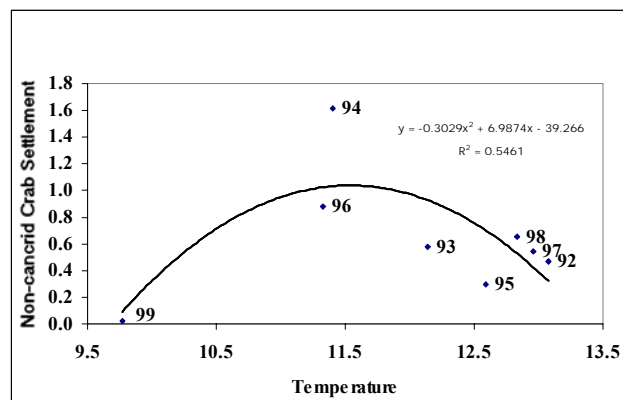
Figure 4 Seasonal (April 30 to August 13) settlement of larvae of non-cancrid (porcellanid, grapsid, pagurid, and majid) crab settlement on brush collectors during 1992-1999 at Bodega Head with seasonal average of temperature at the Bodega Marine Laboratory

In recent years there also has been an intensive oceanographic sampling program to determine how variability in local upwelling winds influences primary and secondary productivity in the Pt. Reyes area. In the NSF-funded CoOP WEST study (Wind Energy and Shelf Transport) collaborators from Scripps Institution of Oceanography, San Francisco State University, University of California, Davis and University of Nevada are using coastal radar (CODAR) and acoustic current profilers to determine circulation, moorings to record winds and biological productivity, and annual oceanographic sampling from research vessels to observe spatial changes in biological productivity and concurrent physical conditions. The same mechanism that drives larval supply to the coast also influences primary and secondary productivity. The poleward, alongshore flow during upwelling relaxation can be seen in the surface currents indicated by CODAR (Figure 5). The WEST program is studying increases in primary and secondary productivity during these relaxation events using data from field surveys and moorings north of Pt. Reyes.

In another study, the National Marine Fisheries Service has recently extended their sampling of juvenile salmon from the bay into the nearshore ocean They have shown that juvenile chinook salmon migrate through the bay rapidly while growing little, then depend on ocean prey resources to begin rapid growth (see MacFarlane and Norton 2002). The potential benefits of combining these kinds of sampling are indicated in an example. Since NMFS had sampled juvenile salmon in 1998 and 1999, and the former was the last year of an El Niño, while the latter was a strong La Niña, they were interested in testing the effects of El Niño on the growth of juvenile salmon. They obtained the surprising result that there was little difference in juvenile salmon growth rate during these two years (MacFarlane and others 2002). A possible explanation for this observation is that while 1999 is an example of a non-El Niño year, it may be too good.   High upwelling may have led to greater biological productivity, but as noted in regard to Figure 3, the strong upwelling flows may have transported that production offshore so that it was not available to juvenile salmon entering the gulf.
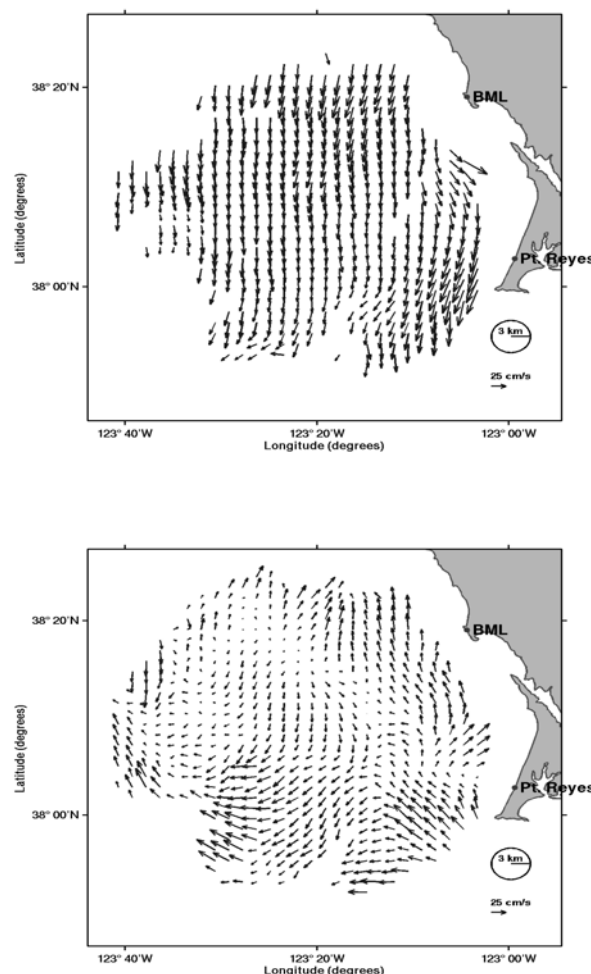
Figure 5 Preliminary results from the NSF CoOP WEST study. Surface currents as indicated by CODAR (Coastal high frequency radar) during strong upwelling (southward) winds on July 14, 2001 (A) and little or no wind, that is, a "relaxation" period on July 6, 2001 (B) (plot by D. Kaplan). During active upwelling, nutrients are brought to the surface and transported to the south and offshore, resulting in little detectable primary productivity. During relaxation, dominant flows are slower and to the north, resulting in rapid plankton blooms.

Summary

In summary, our understanding of ocean influences on salmon has increased dramatically in the past 10 years, and ongoing research programs with rapidly developing technology indicate that will continue. Varying ocean conditions appear to have a strong effect on local salmon populations, and any science-based management program with an adaptive management orientation would benefit

greatly by accounting for ocean effects through ocean monitoring. Perhaps it is time for management of California salmon and associated freshwater resources, to move beyond the view that we can learn nothing of value about the effects of ocean variability on salmon abundance.

Acknowledgements

References

Batdchelder HP, Barth JA, Kosro PM, Strub PT, Brodeur RD, Peterson WT, Tynan CT, Ohman MD, Botsford LW, Powell TM, Schwing FB, Ainley DG, Mackas DL, Hickey BM, Ramp SR. 2002. The GLOBEC Northeast Pacific California Current System Program. Oceanography 15:36–47.

Botsford LW, Lawrence CA. 2002. Patterns of covariability among California Current chinook salmon, coho salmon, Dungeness crab and physical oceanographic conditions. Prog Oceanog 53:283–305.

Brodeur RD, Frost BW, Hare SR, Francis RC, Ingraham WJ Jr. 1996. Interannual variations in zooplankton biomass in the Gulf of Alaska and covariation with California Current zooplankton biomass. CalCOFI Report 37. p 80–99.

Cramer SP. 1992. Contribution of Sacramento Basin hatcheries to ocean catch and river escapement of fall chinook salmon. Report to California Department of Water Resources. 113 p + appendices.

Francis RC, Hare SR, Hollowed AB, Wooster WS. 1998. Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. Fisheries Oceanography 7:1–21.

Lundquist CJ, Botsford LW, Morgan LE, Diehl JM, Lee T, Lockwood DR, Pearson EL. 2000. Effects of El Niño and La Niña on local invertebrate settlement in northern California. CalCOFI Report 41:167–76.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Am Met Soc 78:1069–79.

MacFarlane RB, Norton EC. 2002. Physiological ecology of juvenile chinook salmon (*Oncorhynchus tshawytscha*) at the southern end of their distribution, the San Francisco Estuary and Gulf of the Farallones, California. Fishery Bulletin 100:244–57.

MacFarlane RB, Ralston S, Norton EC, Royer C. 2002. Influences of the 1997–1999 El Niño -La Niña on juvenile chinook salmon off central California [abstract]. 4th Annual Salmon Ocean Ecology Meeting. Available via the Internet at: http://www.pfeg.noaa.gov/events/SalmonMeeting/. Accessed 9 Aug 2002.

Polovina JJ, Mitchum GT, Graham NE, Craig MP, Demartini EE, Flint EN. 1994. Physical and biological consequences of a climate event in the central North Pacific. Fisheries Oceanography 3:15–21.

Polovina JJ, Mitchum GT, Evans GT. 1995. Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the Central and North Pacific, 1960-1988. Deep-Sea Research 42: 1701–16.

Roemmich D, McGowan JA. 1995. Climate warming and the decline of zooplankton in the California Current. Science 267:1324–6.

Taylor JE. 1999. Making salmon: an environmental history of the Northwest Fisheries Crisis. Seattle (WA): University of Washington Press. 421 p.

Venrick EL, McGowan JA., Cayan DR, Hayward TL. 1987. Climate and chlorophyll-*a*: long term trends in the central North Pacific Ocean. Science 238:70–2.

SCIENTIFIC COMMUNITY NEWS

IEP Support for Graduate Research

Ted Sommer (DWR), tsommer@water.ca.gov

As a recent beneficiary of the linkages between IEP and academic institutions, I have had a first hand experience in observing the major role that our organization has had in supporting research by graduate students on the Pacific Coast. Although IEP goals do not explicitly include academic work, IEP continues to provide funding, samples, and data for many local students doing graduate and post-graduate research. The following is at least a partial list of those students who have received IEP support including substantial funding, samples or data. The list was compiled based on input from staff from DFG, DWR, U.S. Environmental Protection Agency, U.S. Geological Survey, U.C. Davis, San Francisco State University, Stanford University, and University of Washington. My apologies to anyone that I have omitted. Note that CALFED funded projects were not included unless the research was conducted with the help of IEP resources.

IEP cannot claim credit for all of the data or support that these students received; however, it is obvious from this list that IEP's effects on university science are far reaching. Seven universities, two states, 40 students...and counting.

Sacramento State University

Fred Feyrer
MS, Suisun Marsh fish diets

Amy Harris
MS, fish ecology

Nina Kogut
MS in progress, sturgeon ecology

Cindy Messer
MS in progress, mitten crab ecology

Matt Nobriga
MS, delta smelt diets

Steve Slater
MS in progress, goby ecology

Tanya Veldhuizen
MS in progress, mitten crabs ecology

San Francisco State University

Paola Bouley
MS in progress, zooplankton life history

Lenny Grimaldo
MS in progress, flooded islands

Diego Holmgren
Post-Doc in progress, fish abundance and distribution

Rian Hooff
MS in progress, zooplankton predation

Heather Peterson
MS in progress, benthic invertebrate ecology

University of California at Berkeley

Peter Weber
PhD, salmon otolith microstructure

University of California at Santa Cruz

Mike Murrell
PhD, microbial foodwebs

University of California at Davis

Jamie Anderson
PhD, salmon/hydrodynamics model

Donald Baltz
PhD, Suisun Marsh/tule perch

Michael Banks
Post-Doc, salmon genetics

Bill Bennett
PhD, fish ecology

Scott Blankenship
PhD, salmon genetics

Robert Daniels
PhD, Suisun Marsh/splittail

Bruce Herbold
PhD, Suisun Marsh fish communities

Joan Lindberg
  PhD, delta smelt culture
Curtis Loeb
  PhD, hydrodynamics
Randy Mager
  PhD, delta smelt culture
Scott Matern
  PhD, Suisun Marsh/goby ecology
Lesa Meng
  PhD, Suisun Marsh ecology
Robert Schroeter
  PhD in progress, Suisun Marsh ecology
Pete Smith
  PhD, 3D modeling of San Francisco Bay
Ted Sommer
  PhD, Yolo Bypass floodplain ecology
Tina Swanson
  Post-Doc, Delta fish physiology
Cincin Young
  PhD, Delta fish physiology

University of Washington

Jason Toft
MS, flooded island invertebrates

Stanford University

Matt Brennan
  PhD in progress, Suisun Bay boundary layer dynamics
Jeremy Bricker
  PhD in progress, Suisun Bay boundary layer dynamics
Jon Burau
  PhD in progress, Suisun Bay hydrodynamics
Ed Gross
  PhD, 3D modeling of estuarine circulation
Jessica Lacy
  PhD, circulation and transport
Lisa Lucas
  PhD, modeling of phytoplankton dynamics
Nancy Monsen
  3D modeling of the Delta
Mark Stacey
  PhD, estuarine turbulence and circulation)
Jan Thompson
  PhD, benthic grazing

Research Published the Open Literature in 2002

Lauren Buffaloe (CALFED) buffaloe@water.ca.gov

Several IEP-affiliated scientists recently published papers in *Estuaries*, *Limnology and Oceanography,* and the *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*. Congratulations to all authors for bringing the published results of their peer-reviewed work to a wider audience via the open literature.

- Kimmerer WJ, Bennett WA, Burau JR. 2002. Persistence of tidally-oriented vertical migration by zooplankton in a temperate estuary. Estuaries 25(3):359–71.

Full paper available on-line at:
http://online.sfsu.edu/~kimmerer/Files/Kimmerer2002.pdf

- Bennett WA, Kimmerer WJ, Burau JR. 2002. Plasticity in vertical migration by native and exotic fishes in a dynamic estuarine low-salinity zone. Limnol Oceanogr 47:1496–1507.

- Müller-Solger AB, Jassby AD, Müller-Navarra DC. 2002. Nutritional quality of food resources for zooplankton (*Daphnia*) in a tidal freshwater system (Sacramento–San Joaquin River Delta). Limnol Oceanogr 47:1468–76.

- Jassby AD, Cloern JE, Cole BE. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. Limnol Oceanogr 47(3):698–712.

- Cloern JE, Canuel EA, Harris D. 2002. Stable carbon and nitrogen isotope composition of aquatic and terrestrial plants of the San Francisco Bay estuarine system. 47(3):713–29.

Abstracts for the above papers available on-line at: http://aslo.org/index2.html.

- Sobczak WV, Cloern JE, Jassby AD, Müller-Solger AB. 2002. Bioavailability of organic matter in a highly disturbed estuary: the role of detrital and algal resources. PNAS 99(12):8101–5.

Abstract available on-line at http://www.pnas.org/cgi/content/abstract/99/12/8101.

Early Life History of Fishes in the San Francisco Estuary and Watershed
Symposium and Proceedings Volume

Sponsored by the Interagency Ecological Program and the CALFED Science Program
To be held in conjunction with the American Fisheries Society, Larval Fish Conference
August 20-23, 2003 University of California, Santa Cruz

The symposium proceedings will be published by the American Fisheries Society in late 2003 and will be edited by Frederick Feyrer (Dept. of Water Resources), Larry Brown (U.S. Geological Survey), James Orsi (Dept. of Fish and Game, retired), and Randall Brown (Dept. of Water Resources, retired). Contributed papers to date are listed below.

For more information and updates contact Frederick Feyrer (ffeyrer@water.ca.gov) or visit the following web sites:
IEP Early Life History Symposium: http://iep.water.ca.gov/2003_elh/
AFS 2003 Larval Fish Conference: http://www.lfc2003.com

Larval fish assemblages of San Francisco Bay
M. McGowan (San Francisco State University, Romberg Tiburon Center)

Ecology of larval herring (*Clupea harengus*) in San Francisco Bay
S. Bollens and A. Sanders (San Francisco State University, Romberg Tiburon Center)

Salinity influences on reproductive outcome in San Francisco Bay Pacific Herring
F. Griffin, G. Cherr, E. Smith, C. Vines, and H. Brown (U.C. Davis, Bodega Marine Lab)

Larval anchovy ecology in San Francisco Bay
M. McGowan (San Francisco State University, Romberg Tiburon Center)

Characteristics of atherinid spawning and rearing habitat in east-central San Francisco Bay
A. Jahn, J. Amdur, and J. Zaitlin (Port of Oakland)

Springtime trends in larval fish distribution and abundance in the San Francisco Estuary
M. Dege and R. Mayfield (CA Dept. Fish and Game)

Spatial and temporal trends in larval fish abundance in the Sacramento-San Joaquin Delta
L. Grimaldo, R. Miller, C. Peregrin, and Z. Hymanson (CA. Dept. Water Resources)

Ecological segregation between native and alien larval fish assemblages in the southern Sacramento-San Joaquin Delta
F. Feyrer (CA Dept. Water Resources)

Growth of larval striped bass in the San Francisco Estuary, California
S. Foss and L. Miller (CA Dept. Fish and Game)

Vertical distribution of larval delta smelt and striped bass in the Sacramento-San Joaquin Delta, California
A. Rockriver and K. Fleming (CA Dept. Fish and Game)

Egg and larval dispersion in a tidal channel with diversions using a particle tracking model
C. Harrison and C. Enright (CA Dept. Water Resources)

Feeding ecology of larval fishes in the entrapment zone of the San Francisco Estuary, California
J. Hobbs and W. Bennett (UC. Davis, Bodega Marine Lab)

Feeding ecology of juvenile striped bass
J. Arnold and L. Miller (CA Dept. Fish and Game)

Does size, taxa or color matter? Evaluating fish-larvae light trap efficiency in the northern Sacramento River system
M. Marchetti, E. Esteban, M. Limm, and R. Kurth (CA State University, Chico)

Spawning by native and alien fish on a restored floodplain: evidence from larvae
P. Crain and P. Moyle (U.C. Davis)

Temporal dynamics of early life stages of fish in large river floodplain of the San Francisco Estuary
T. Sommer and B. Harrell (CA Dept. Water Resources)

Estimating growth rates of young Central Valley chinook salmon using otolith microstructures
R. Titus (CA Dept. Fish and Game)

Factors influencing the feeding behavior of larval delta smelt (*Hypomesus transpacificus*)
B. Bridges and J. Lindberg (U.C. Davis)

Embryogenesis and larval development of delta smelt
R. Mager (CA Dept. Water Resources)

Lethal and sublethal effects of estenvalerate and diazinon on splittail larvae
S. Teh, G. Zhang, T. Kimball, and F.C. Teh (U.C. Davis)

Tidal and diel variability in fish entrainment through screened and unscreened agricultural diversion siphons in the lower Sacramento River
M. Nobriga, Z. Matica and Z. Hymanson (CA Dept. Water Resources)

Temperature effects on growth of larval and juvenile green sturgeon
P. Allen and J. Cech (UC. Davis)

Lower Feather River fishes: composition, distribution and associations with environmental variables
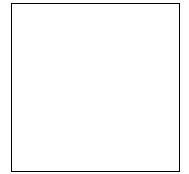A. Seesholtz and B. Cavallo (CA Dept. of Water Resources)

For information about the Interagency Ecological Program, visit our website on-line at http://www.iep.water.ca.gov. Readers are encouraged to submit brief articles or ideas for articles.   All correspondence, including submissions for publication, requests for copies, and mailing list changes should be addressed to Lauren Buffaloe, California Department of Water Resources, 3251 S Street, Sacramento, CA, 95816-7017.

IEP NEWSLETTER

Interagency Ecological Program for the San Francisco Estuary

The Interagency Ecological Program for the San Francisco Estuary
is a cooperative program of the

California Department of Water Resources	California Department of Fish and Game
State Water Resources Control Board	US Fish and Wildlife Service
US Bureau of Reclamation	US Geological Survey
US Army Corps of Engineers	US Environmental Protection Agency

National Marine Fisheries Service